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A MULTISTAGE R & D PROJECT SELECTION MODEL WITH MULTIPLE OBJECT--ETC(U)

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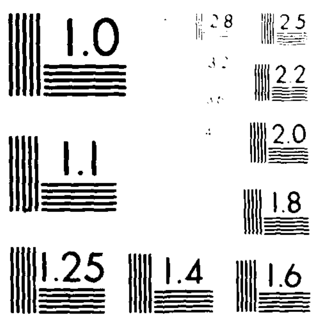
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THOMAS CRAIG HARRINGTON. A Multistage R&D Project Selection Model with Multiple Objectives (Under the direction of WILLIAM A. FISCHER.)

This dissertation presents a multiple objective, zero-one mathematical programming model for the stochastic, multistage R&D project selection and resource allocation problem. The model is intended for those research and development activities which have a certain degree of autonomy in the selection of their research portfolio and which concentrate efforts in applied research or development projects.

Each feature of the proposed model is designed to incorporate realistic aspects of the R&D decision making process. First, the model includes an integer goal programming formulation which enables the formal incorporation of multiple, noncommensurate objectives along with integer treatment of possible projects. Second, decision tree planning techniques are used to represent the sequential aspects of allocating scarce resources over the planning horizon, to reflect various project and goal relationships, and to incorporate probabilistic future events and outcomes. Third, simulation techniques are used to convert the probabilistic parameters into deterministic inputs for the mathematical formulation. Finally, the model includes a heuristic based solution algorithm involving system constraint partitioning procedures, and iterative one-pass variable selection and solution variable exchange routines to enable the efficient solution of realistic size problems.

Example problems are presented to examine the conceptual utility of the proposed model. Practical utility is demonstrated through testing the model against recent state-of-the-art project selection

techniques. Finally, model feasibility is demonstrated through an actual application and appraised through interviews with R&D administrators.

Applications of the model to other types of resource allocation and capacity management problems are proposed as areas for further research.

A MULTISTAGE R&D PROJECT SELECTION MODEL WITH MULTIPLE OBJECTIVES

by

Thomas C. Harrington

A Dissertation submitted to the faculty of
the University of North Carolina in partial fulfillment of
the requirements for the degree of Doctor of Philosophy
in the School of Business Administration

Chapel Hill

1979

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I wish to express my warmest thanks to my parents, who set exemplary standards and provided me with my most important education; to my late sister, Bonnie, who taught me the real meaning of courage; and to my father-in-law and late mother-in-law, who constantly encouraged us in this endeavor and our career.

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CHAPTER I

INTRODUCTION

> "It should be obvious that the performance of a research organization can be no better than the projects selected as inputs to the R&D system. Working on the wrong project is wasteful, and the resulting penalty is a low return on R&D investment. No wonder, then, that project selection is perhaps the most critical step of the entire R&D process."
>
> (Introduction to a Collection of Papers on Project Selection, Research Management, Vol. 14, September, 1971, p. 24)

The R&D project selection decision is concerned with the allocation of scarce organizational resources such as money, skills, and equipment, among a set of proposals for performing research or development projects.[1] The selection decision is important to sponsoring and performing agencies since the portfolio of projects selected typically represents considerable risk and investment. To illustrate the magnitude of expenditures in aggregate terms, U.S. Government agencies, industries, universities and nonprofit enterprises invested $ 40.8 billion in R&D projects during 1977[2] and are expected to invest $ 45.2 billion in 1978.[3]

The selection decision is a complex and difficult process due to the nature of the R&D environment. Generally, the number of project proposals together with existing projects which must be considered, make demands on resources in excess of current and forecasted capabilities;[4] simply stated, most R&D activities are faced with more proposals for projects than resources can support at any given time. Furthermore, R&D projects must be evaluated, selected and measured against multiple and often conflicting economic and non-economic objectives. In addition, the very nature of R&D to push forward the existing scientific and technological state-of-the-art introduces uncertainty into the project selection process.[5] Thus, proposal estimates for key items such as the probabilities of technical and commercial success, timing and levels of income and cost streams, project duration, resource usage rates and resource availabilities can be difficult to accurately determine.

Many qualitative and quantitative techniques have been developed in the past twenty-five years to assist R&D managers in the project selection and resource allocation decision. In a 1964 survey, Baker and Pound[6] cited eighty-two sources in the literature directly related to project selection; ten specific models were reviewed as being representative of the more than fifty techniques available. Cetron, Martino and Roepcke[7] identified and evaluated thirty techniques in their 1967 survey. In 1971, Gear, Lockett and Pearson[8] reviewed nine mathematical programming models dealing with the portfolio selection and resource allocation problem. Souder[9] singled out forty-one models as being representative of the more than one hundred techniques known to exist by 1972. In that same year, Baker and Freeland[10] provided a comprehensive assessment of the state-of-the-art models. Their findings echoed those of the other reviewers and practitioners: while some excellent techniques have been developed to address specific factors of the problem, existing models are not being used by research and development managers because of key limitations such as:

1) Inadequate treatment of multiple objectives, including both economic and noneconomic criteria.

2) Inadequate treatment of the time variant property of data and criteria.

3) Failure to consider the experience and knowledge of R&D managers, scientists and engineers.

4) Inability to represent, establish and maintain balance in the R&D program.

5) Inadequate treatment of risk and uncertainty.

6) Failure to represent project interrelationships with respect to both value contribution and resource utilization.

Interviews conducted with a small but representative sample of organizations involved in R&D activities as part of this research have found agreement with these findings of other researchers that quantitative project selection models are not being used in the field. The most significant reason for this lack of application is indeed the failure of the model builders to account for realism with respect to multiple objectives, multiple stages in project evolution and uncertainty. However, three additional reasons were identified during the interview sessions which provide additional insight into the R&D decision making process. First, in the case of the R&D laboratories of a large textile firm and a pharmaceutical company, there is a lack of awareness of management science models proposed as decision aiding tools. Second, in the case of a nonprofit research institute and the research laboratory of a government regulatory agency, project selection occurs, to some extent, at the client or sponsoring activity level rather than within the research organization and the R&D organization has little alternative but to accept mandated projects.[11] Third, especially in the case of the pharmaceutical company, project proposal data, in the laboratory visited, is not collected with the detail necessary for use of quantitative selection models. It should be noted that this research laboratory is principally engaged in exploratory research for the advancement of medicine knowledge rather than in applied research or development work associated with specific end use items, and because project proposals for exploratory research are by their very nature, ill defined, it appears that formal selection techniques have limited applicability in this type of environment.

In view of the limitations or the utility of the present state-of-the-art models, the objective of this research is stated as follows:

> Develop a workable, multicriteria mathematical programming, format for selecting interdependent R&D projects over a multiperiod planning horizon.

The managers and directors of the R&D organizations interviewed during the course of this research gave particular encouragement to the pursuit of this objective and contributed towards the following statement of the scope of model applications:

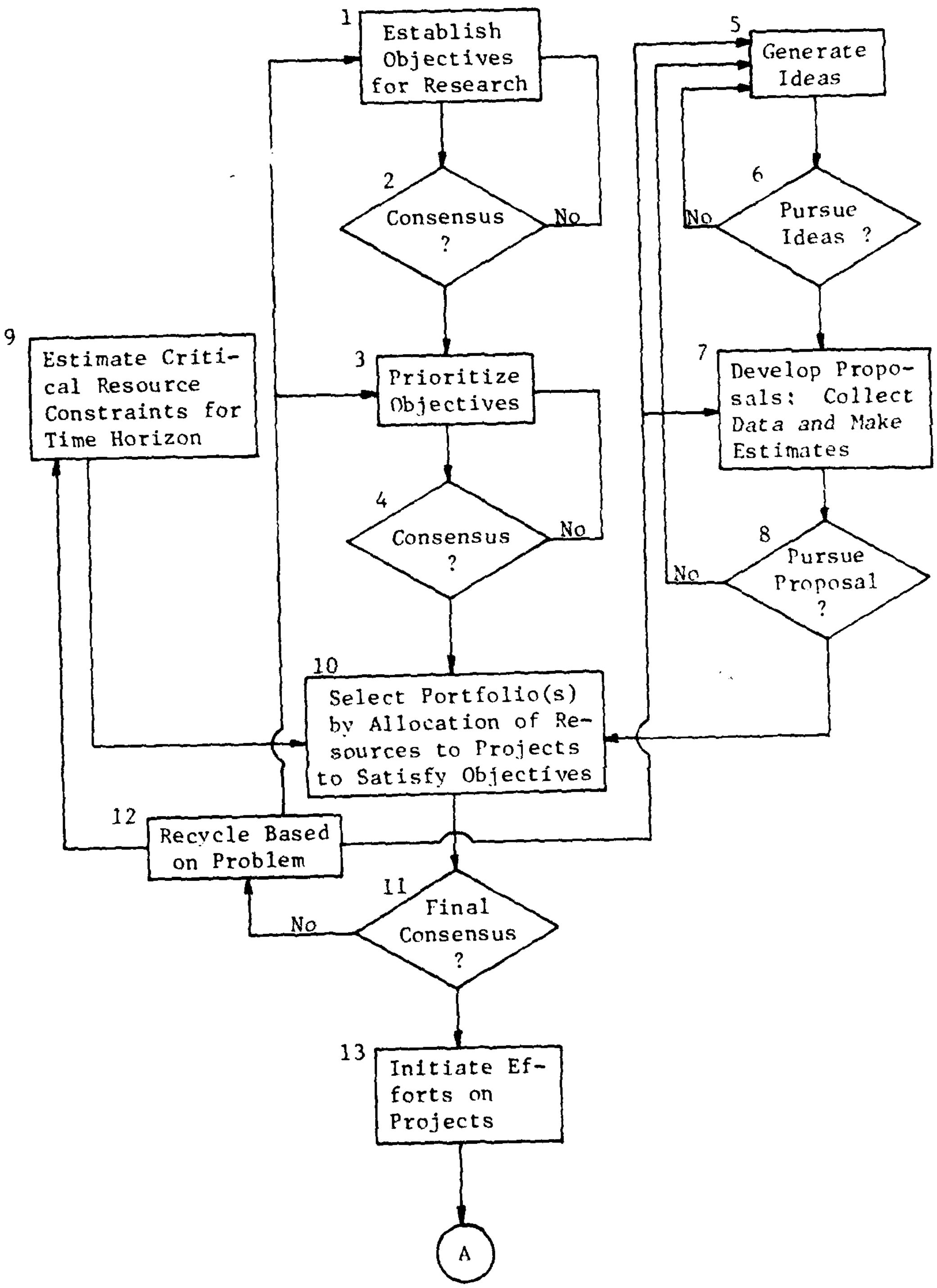
> The project selection and resource allocation model is designed and intended for those R&D activities which have a certain degree of autonomy in the selection of their research portfolio, and which concentrate efforts on applied research or development projects associated with clearly defined end uses.

The following section serves to amplify on the purpose, scope and contribution of this research.

Purpose and Scope of This Research

In order to establish the contribution of this research, it is important to view the project selection and resource allocation decision as an integrated part of a larger process that involves idea generation and handling, project proposal evaluation, project initiation and control, and project completion and termination. Descriptive studies by Dean,[12] Souder,[13] Beattie and Reader,[14] and Brandenburg[15] discuss these essential features and are used, in part, to diagram the total project selection and evaluation process as shown in Figure 1-1. In addition, steps concerned with establishing research program objectives (boxes 1 and 2), and their relative priorities (boxes 3 and 4), as well as a representation of component interactions through feedback mechanisms, have been added to embed the research in a realistic setting. As a first step, the organization develops objectives for the research program and prioritizes these objectives (boxes 1 through 4). Comparative techniques such as Q-Sort and pairwise comparison by forced choice have been applied in these decision stages.[16] The next series of steps involve idea generation and proposal development (boxes 5 through 8). Qualitative techniques such as scoring methods and economic models have been used in these stages to construct indexes of project worth.[17] Although the above techniques have been suggested for the project selection decision stage by, for instance, Souder,[18] Moore and Baker,[19] and Villers,[20] because of their inability to simultaneously

Figure 1-1
The R&D Process



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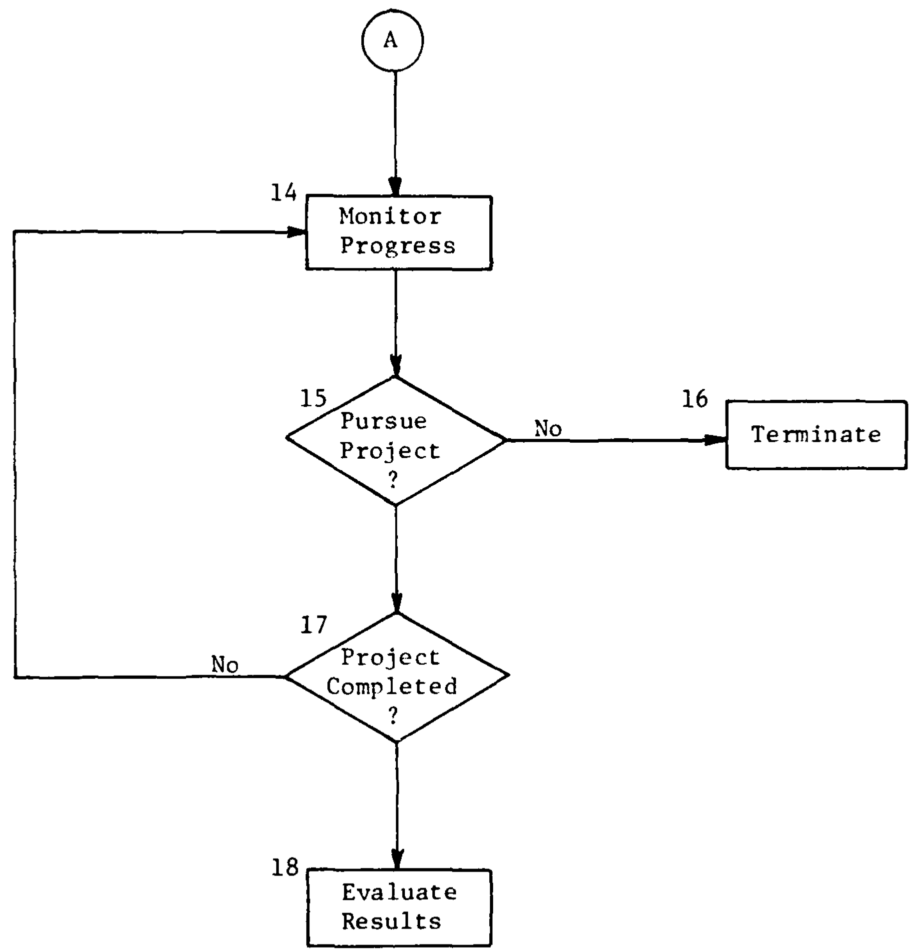

consider resource constraints (box 9), these models are likely to generate portfolios with a sub-optimal allocation of resources. Quantitative techniques based on mathematical programming have been developed for the project selection and resource allocation stage (box 10) by, for example, Asher[21] and Beged-Dov,[22] but are restricted in their utility because they tend to allocate resources to a portfolio of projects by optimizing a single or unidimensional objective function. Further, none of the quantitative techniques surveyed, including those that address noncommensurate multiple criteria, are designed to be integrated into the total R&D process as either the multistage nature of discrete projects and multiple resource constraints are ignored and/or uncertainty in the project proposal data parameters is not considered. The purpose of this research is therefore to fill a void in the selection process through development of a multistage, multiple objective mathematical model for the box 10 decision stage.

It is further proposed that the model is useful as an analytic technique to interact with the resource determination, proposal development, and multiple objective generation stages. As an example, even if economic and noneconomic criteria can be established within an R&D group, it remains unlikely that consensus can be reached on the relative importance of the group's goals, especially in a hierarchical organization structure. If consensus remains blocked after several iterations through the decision process represented by boxes 3 and 4 of Figure 1-1, the group has been divided into proponents of two or more conflicting priority structures. At this point, it is suggested that the present model be used to generate portfolios of projects for each set of priority rankings. Since the model provides the decision makers with additional information regarding goal attainment levels for corresponding portfolios and priority structures, consensus could be facilitated through trade-off analysis or identification and evaluation of dominant portfolios and/or projects. Similarly, decision makers responsible for establishing resource levels may use the model to analyze multiple goal attainment levels associated with portfolios generated for various resource constraint sets. Alternatively, changes in resource levels over the planning horizon may be suggested in selection of a particular portfolio provided that some resource flexibility exists. Finally, decision makers responsible for estimating probabilistic outcomes (boxes 7 and 8, Figure 1-1) could benefit from using the model to generate alternative portfolios for dominant futures or for various changes in the estimates. Statistical analysis and group interactions could then be used in searching for dominant portfolios and/or projects for construction of the final research effort.

In summary, the contribution of this research effort is a multi-stage, multiple objective R&D project selection model designed to interact with portions of the larger R&D project selection and evaluation system. While the research focuses on the project selection problem, the model is also adaptable for the termination decision (boxes 15 and 16, Figure 1-1). That is, in addition to new proposals for the R&D effort, existing projects may also be considered in the selection decision without constraint mechanisms forcing their acceptance in the final portfolio. Model solutions failing to accept an existing project based upon the multiple goal attainment levels would suggest project termination prior to planned completion.

The steps involved with initiation of effort on selected projects, project control, completion and evaluation of results (reference boxes 13, 14, 17 and 18, Figure 1-1) are important stages in the total process but are beyond the scope of this research.

Summary of the Chapters

Chapter II presents a survey of the principal techniques proposed in the literature for the R&D project selection and resource allocation problem. From this review, a set of prescriptions for a general analytic technique are developed.

Chapter III presents the basic development of the multistage, multiple objective model and solution algorithm. The complete model includes:

1) Integer goal programming formulation which enables the formal incorporation of multiple objectives along with a recognition of the need for integer rather than linear treatment of possible projects.
2) Decision tree planning of R&D projects over a multiperiod planning horizon. This structure is used for representation of the sequential aspects of allocating scarce resources over the planning horizon, to reflect various project and goal relationships, as well as incorporating chance future events and probabilistic outcomes.
3) Simulation of the chance future events and project outcomes to convert stochastic parameters into deterministic inputs for the integer goal programming model.

4) Heuristic based solution algorithm involving selected system constraint partitioning procedures, and iterative one-pass variable selection and solution variable exchange routines to enable the rapid solution of realistic size problems.

5) Statistical analysis of model results.

In Chapter IV, a hypothetical case study is presented to demonstrate the application potential of the model for portfolio selection and resource allocation decision processes.

Chapter V presents several applications of the model, three of which represent validity and efficiency evaluations through comparisons with other state-of-the-art zero-one, dynamic programming, and integer goal programming models. An actual application for project selection and resource allocation decision processes in the R&D laboratory of a large textile firm is also included. Finally, a summary of the findings of the interview sessions with the directors of five R&D organizations concerning additional applications and evaluation of model feasibility is presented.

Chapter VI discusses conclusions and suggests areas for further research.

Footnotes

[1]B. V. Dean, Evaluating, Selecting and Controlling R&D Projects, AMA Research Study 89 (New York: American Management Association, Inc., 1968), p. 65.

[2]National Science Foundation, National Patterns of R&D Resources, Funds, and Manpower in the United States, 1953-1977, NSF 77-310 (Washington, D.C.: U.S. Government Printing Office, 1977), p. vi.

[3]C.J. Mosbacher, "Forecast '78: $45.2 Billion for R&D," Research/Development, Vol 29 (January, 1978), pp. 23-24.

[4]A.E. Gear, "A Review of Some Recent Developments in Portfolio Modelling in Applied Research and Development," IEEE Transactions on Engineering Management, Vol. EM-21 (November, 1974), pp. 119-125.

[5]J.R. Moore, and N.R. Baker, "Computational Analysis of Scoring Models for R&D Project Selection," Management Science, Vol. 16 (December, 1969), pp. B212-B232.

[6]N.R. Baker, and W.H. Pound, "R and D Project Selection: Where We Stand," IEEE Transactions on Engineering Management, Vol. EM-11 (December, 1964), pp. 124-134.

[7]M.J. Cetron, J. Martino, and L. Roepcke, "The Selection of R&D Program Content - Survey of Quantitative Methods," IEEE Transactions on Engineering Management, Vol. EM-14 (March, 1967), pp. 4-13.

[8]A.E. Gear, A.G. Lockett, and A.W. Pearson, "Analysis of Some Portfolio Selection Models for R&D," IEEE Transactions on Engineering Management, Vol. EM-18 (May, 1971), pp. 66-76.

[9]W.E. Souder, "A Scoring Methodology for Assessing the Suitability of Management Science Models," Management Science, Vol. 18 (June, 1972), pp. B526-B541.

____________, "Comparative Analysis of R&D Investment Models," AIIE Transactions, Vol. 4 (March, 1972), pp. 57-64.

[10]N.R. Baker, and J.R. Freeland, "Recent Advances in R&D Value Measurement and Project Selection Methods," Presented at the 41st National Meeting of the Operations Research Society of America, New Orleans, La., April, 1972.

[11]Since Federal Government R&D agencies and independent non-profit research institutes currently account for just 19% of the U.S. National R&D effort (see reference in Footnote 2) it follows that only a small number of R&D activities would not use quantitative selection models because of this third reason. In other

words, a large majority of R&D activities are faced with decisions involving selection of a portfolio for research rather than having a portfolio totally mandated by using activities. In the case of industry, although a laboratory might be told what to do by corporate headquarters, somewhere within the firm, project selection is performed.

[12]Dean.

[13]W.E. Souder, "Field Studies with a Q-Sort/Nominal Group Process for Selecting R&D Projects," Research Policy, Vol. 4 (April, 1975), pp. 172-188.

[14]C.J. Beattie, and R.D. Reader, Quantitative Management in R&D (London: Chapman and Hall, Ltd., 1971), pp 1-133.

[15]R.G. Brandenburg, "Project Selection in Industrial R&D: Problems and Decision Processes," Research Program Effectiveness, ed. M.C. Yovits, et. al. (New York: Gordon and Breach Scientific Publishers, Inc., 1966), pp. 14-40.

[16]Souder, "Field Studies with a Q-Sort/Nominal Group Process for Selecting R&D Projects."

W.E. Souder, "Achieving Organizational Consensus with Respect to R&D Project Selection Criteria," Management Science, Vol. 21 (February, 1975), pp. 669-681.

[17]C.M. Mottley, and R.D. Newton, "The Selection of Projects for Industrial Research," Operations Research, Vol. 7 (November-December, 1959), pp. 16-22.

R. Villers, Research and Development: Planning and Control (New York: Financial Executives Research Foundation, Inc., 1964), pp. 43-44.

[18]Souder, "Field Studies with a Q-Sort/Nominal Group Process for Selecting R&D Projects."

[19]Moore and Baker.

[20]Villers, pp. 43-44.

[21]D.T. Asher, "A Linear Programming Model for the Allocation of R&D Effort," IRE Transactions on Engineering Management, Vol. EM-9 (December, 1962), pp. 154-157.

[22]A.G. Beged-Dov, "Optimal Assignment of Research and Development Projects in a Large Company Using an Integer Programming Model," IEEE Transactions on Engineering Management, Vol. EM-12 (December, 1965), pp. 138-142.

CHAPTER II

SURVEY OF THE PRINCIPAL TECHNIQUES AND MODEL PRESCRIPTIONS

"It is important to ensure that a (project selection) system is set up which does not reject half baked ideas solely because they lack baking, but yet does not spend so much effort on evaluating possible ideas in depth that there is hardly any effort left to do the research."

(Beattie and Reader, Quantitative Management in R&D, p.27)

Prior to World War II and in the early post-war years, companies with large enough R&D laboratories could choose the product line or area in which to devote its R&D resources and expect to reap considerable benefits.[1] During this period, Rubenstein observed that reasonably efficient research endeavors produced benefits that far out-weighed the costs and thus, most companies were not concerned with precise methods of project selection.[2] As the post-war markets matured in the 1950's, companies began to see a relationship between intensified R&D efforts and corporate growth.[3] Brandenburg noted in his 1966 descriptive study[4] that the optimism, permissiveness and faith of the post-World War II industrial research revolution gave way to emphasis on measurement and control in budgeting resources among alternative R&D project opportunities. As a result, formal project selection methods were desired by R&D managers as decision aiding tools. In attempting to meet this need, management scientists and some practitioners developed techniques that can be generally categorized as scoring models, comparative methods, economic index and mathematical programming models. These are reviewed in the next four sections. Following this survey, two additional sections are devoted to reviewing techniques designed to incorporate the dynamic nature and uncertainty associated with R&D projects and methods which address the multiple criteria problem.

Scoring Models

Scoring models are among the earliest formal approaches to addressing the multiple goals of an R&D group. Methods such as those proposed by Dean and Nishry,[5] Garguilo, et. al.,[6] Mottley and Newton,[7] and Pound,[8] begin with development of a list of all the criteria that are important in choosing projects. For example, the Mottley and Newton model includes promise of success, time to completion, cost of the project, strategic need and market gain as the criteria. Next, numerical scales are assigned to each criterion and a panel of experts are asked to rate each project proposed on the criterion scale. The resultant ratings are then combined in a multiplicative or additive fashion to determine a project score which is used to rank order the projects. The R&D portfolio is determined by successively selecting projects as they appear in the ranking until some constraint such as budget, personnel or facilities is reached.

Scoring models are relatively easy to develop and evidence suggests they have found some use in actual R&D environments, particularly in the evaluation of project proposals and selection of basic research projects.[9] However, Beattie and Reader[10] noted that their inherent simplicity can lead to an unwarranted appearance of validity. Seiler[11] expanded on this point by noting that biases by those making the rating calculations and inconsistency in data accumulation could affect project scores so that projects may appear more or less promising than they really are. A major limitation is that scoring models do not account for project interrelationships with respect to resource utilization.[12] Once a resource constraint becomes binding, the portfolio is determined. Obviously, there could be slack in other resources and a different portfolio could lead to a more optimal allocation. A further problem occurs with mutually exclusive versions of the same project which represent various time durations depending upon the level of resources allocated. Scores can be calculated for each version but the trade-off between resource levels and time durations makes it even more difficult to select the portfolio with the optimum allocation.[13] Also, since the multiple criteria ratings are aggregated into dimensionless score, there can be little analysis of the degree to which the resultant portfolio meets the various organizational criteria. In fact, it could be possible, although unlikely, to construct a portfolio in which every project selected scores low on a critical objective but very high on all other criteria; the end result being a portfolio which does not satisfy the most important objective. In summary, scoring models are best utilized for the screening of ideas and proposals (boxes 5-8, Figure 1-1) but not for the selection of projects and resource allocation decisions.

Comparative Methods

Comparative methods such as Souder's Q-Sort with nominal group interactive processes,[14] and paired comparison instruments as suggested by Souder[15] and Tauss,[16] represent another class of qualitative techniques in which respondents are required to successively compare a project proposal with another or with a subset of proposals and specify which is preferred with respect to a single criterion. A preference rank ordering results for project selection and development of the research portfolio. If multiple criteria are to be considered, separate Q-Sorts or paired comparison experiments are conducted for each criterion and a project profile is developed for management evaluation,[17] or the sorter is forced to intuitively incorporate multiple criteria into the selection procedure in an aggregate manner.[18] In using these techniques for project selection, criteria are rated by assigning number values on a ratio scale through pairwise comparison experiments. Project subscores are then determined by a pairwise comparison of projects for each criterion. A final project score is determined by summing the products of criterion weights and project subscores. The project scores can then be rank ordered for project selection.

The disadvantage of these methods is similar to that of the scoring models with respect to resource allocation and analysis of goal attainment levels. Another disadvantage of the comparative approaches occurs when a new project is added to the set of projects considered for the portfolio. In this case, the entire exercise must be repeated since an additional project will affect the preference rankings of other projects.[19] New projects do not require a repeat of the selection procedure when scoring models are used as project scores are determined independently. However, repeating any algorithm used to select projects when new proposals are added to the list may be advantageous when the process is conducted on a semicontinuous basis, especially with the quantitative models that also address the resource allocation problem.

The main contribution of comparative techniques to the total R&D process is not in the project selection area, but rather in the development of multiple criteria and associated priority rankings. That is, they have potential for applications concerning the decision processes represented by boxes 1 through 4 in Figure 1-1.

Economic Index Models

Economic or profitability index models represent another class of techniques introduced in the early 1960's as a way to solve the project selection problem. These models are used to generate indices of the relative worth of projects based on economic factors usually combined in a nonlinear functional form. The indices are then rank ordered for selection purposes or compared against some criterion such as a minimum admissable profit index to determine when projects should be rejected or terminated.[20] Models of this type include project index functions developed by Pacifico,[21] Hart,[22] Villers,[23] and Whaley and Williams;[24] Ansoff's profit figure of merit;[25] Olsen's relative value index;[26] and a profit-cost index function proposed by Hart.[27] These models are generally extensions of simple techniques such as the return ratio used by Bobis, Cooke and Paden[28] in which the project index is constructed as the ratio of the expected future returns to the expected future research costs. As an example of an extended technique, Villers' method develops the index of relative worth as the ratio of the estimated present value of future earnings of a project minus the direct costs of research to the total estimated cost of the R&D project effort. The resulting ratio is converted to an expected value by multiplying by the probabilties of research, development, process and commercial successes. The selection procedure requires rank ordering of the project indices and selecting projects from the top of the list until a total cost constraint prevents further selections.[29] In addition to the basic index methods, other economic models develop project figures of merit based simply on the internal rate of return or project net present value. Souder[30] suggested a more sophisticated technique which combines a Hertz type risk analysis model[31] with Olsen's relative value index method. Still other economic models use the project index or figure of merit as objective function coefficients in mathematical programming formulations which are discussed in the next section.

Although Baker[32] reports some evidence of application of economic index models, there are limitations. First, the models assume that project selection decisions are made based on a single economic criteria, disregarding the noneconomic objectives of the enterprise. Second, constraints other than the research budget are not considered in portfolio construction. Third, economic indices give no guidance as to which version of a project should be selected where the versions represent varying profiles of resource allocation yet yield similar index values.[33] In summary, economic index models best serve for the screening of project proposals or for the termination decision (reference boxes 7, 8, 15, and 16, Figure 1-1) but not for the project selection and resource allocation problem.

Mathematical Programming Models

Mathematical programming models are the most recent class of models proposed for the project selection problem and have the major benefit of addressing the resource allocation decision through equations that constrain an objective function which measures the benefit contribution of a selected portfolio. These models suggest the present state-of-the-art for the decision process represented by box 10, Figure 1-1, and, therefore, a more thorough review of them will be given here. The first linear programming model formulation for R&D project selection is credited to Asher,[34] in which project selection in a pharmaceutical company is accomplished by maximizing the expected discounted net present value of projects subject to manpower and raw material availabilities. Other work such as the models developed by Lockett and Gear,[35] Hamburg,[36] and Bell,[37] incorporate extensions and variations to Asher's formulation. Bell's model which includes future time period resource constraints is presented to illustrate a general formulation:

$$\text{Maximize } Z = \sum_{i=1}^{n} \sum_{j=1}^{m_i} b_{ij} x_{ij} \qquad (2.1)$$

$$\text{Subject to: } \sum_{j=1}^{m_i} x_{ij} \leq 1 \qquad i = 1,\ldots,n., \quad (2.2)$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m_i} a_{ijkp} x_{ij} \leq A_{kp} \qquad k = 1,\ldots,N., \; p = 1,\ldots,P., \quad (2.3)$$

$$x_{ij} \geq 0 \qquad i = 1,\ldots,n., \; j = 1,\ldots,m_i.$$

Where: b_{ij} is the value of version j of project i.

m_i is the number of alternate versions of project i.

n is the number of projects, both on-going and new.

a_{ijkp} is the amount of resource type k planned (or required) for version j of project i in time period p.

A_{kp} is the overall availability of resource type k in period p.

N is the number of resource categories considered.

P is the number of periods in the planning horizon.

Integer (zero-one) programming models such as those of Freeman,[38] Beged-Dov,[39] and Minkes and Samuel[40] were introduced to prohibit the inclusion of fractional projects in the final portfolio. That is, the x_{ij} project version variables are further constrained as follows:

$$x_{ij} = \begin{cases} 1 \text{ if version j of project i is selected,} & \\ 0 \text{ otherwise,} & i = 1,\ldots,n., \\ & j = 1,\ldots,m_i. \end{cases} \qquad (2.4)$$

Before discussing some of the extensions to these basic formulations, it is important to comment on the relative merits of the linear and integer programming approaches. Proponents of the linear formulation (where x_{ij} may take on any value in the continuum $0 \le x_{ij} \le 1$) note that existing linear programming codes efficiently handle large scale problems and provide useful information through sensitivity or post-optimality analysis. However, the linear program results may include fractional projects which enable an optimum allocation of resources providing that the divisability of projects is feasible and desirable, but could lead to difficulties in actual interpretation.[41] Asher[42] suggested that any fractional projects be included in the research effort as partial versions of the original projects. That is, some work should be accomplished on the project in the current period rather than excluding the project entirely and letting slack exist in the available resources. Lockett and Gear[43] suggest that fractional projects may indicate a modified version of the project should be designed which would be of smaller scope than the original project version. It should be noted that in both of these cases the fractional projects selected for research are not the original projects provided as inputs to the model, but rather they actually represent project versions generated by the solution algorithm. In another study, Lockett and Gear[44] rounded fractional projects to the closest integer value (zero or one) for development of the portfolio, although they state that "the approach was not fruitful in finding a stable portfolio." While interpretation of fractional projects is difficult, rounding to integer values is dangerous. As Wagner notes,[45] a rounded solution could be infeasible or it could be feasible but not optimal. Any adjustment to the fractional solution values represents a departure from the original problem. On the other hand, integer formulations are solved by integer programming codes that restrict the problem size and any sensitivity analysis must be accomplished by rerunning the models.[46] Another disadvantage occurs with integer programming algorithms in those instances where the linear solution would result in fractional projects. In these situations, the integer solution will have slack in one or more of the absolute resource constraints. In summary, there appears to be a trade-off between fractional projects with their inherent interpretational difficulties and the ability to handle large problems. Integer programming formulations represent the more realistic project representation, although a means of improving the efficiency of associated solution algorithms should be developed. In this regard, Mandakovic[47] has recently developed an interactive heuristic procedure for a decomposed integer program formulation which is capable of handling very large size problems and is a promising method for single objective project selection applications.

Many extensions have been made to the mathematical programming techniques discussed above. Gear, Lockett and Pearson[48] provide an excellent review and assessment of nine representative formulations. Watters,[49] Brockhoff,[50] and Charnes and Stedry[51] incorporate the use of probabilistic constraint rows to reflect the uncertainty in resource availability. Hess,[52] Rosen and Souder,[53] and Dean and Hauser[54] include a probability of success factor which is multiplied times the project value coefficient in the objective function to allow for technical outcome uncertainty, and Watters[55] suggests the maximization of a portfolio utility function to account for uncertain returns. The techniques developed by Brandenburg and Stedry,[56] Watters[57] and Brockhoff[58] incorporate capital budgeting concepts but are limited in that constraints other than the budget are not addressed. The techniques of Hess,[59] Rosen and Souder,[60] Brockhoff,[61] and Bell[62] allow for the inclusion of alternate versions of projects, compulsory projects, and project interactions. The models proposed by Mandakovic[63] and Baker, et. al.,[64] incorporate the realistic aspects of the decentralized structure of organizational R&D decision making and the corresponding hierarchies.

The major disadvantages of most of the quantitative techniques described in this section are first, a failure to account for the dynamic nature of R&D projects, and second, the reduction of multiple organizational goals to a single, typically economic, objective for optimization. These two aspects of the decision making process are more fully described in the next two sections.

Multistage Project Modeling

Because of the long-term nature of R&D, and the high degree of uncertainty involved, R&D project selection and resource allocation models should account for the multistage, sequential nature of projects and explicitly consider the uncertainty that exists in the project evolution and resource parameters if they are to arrive at a near optimal project selection and resource allocation decision.[65] Dynamic programming formulations (for example, Hess[66] and Rosen and Souder[67]) do address the multistage and sequential nature of many R&D projects. However, these models cannot efficiently handle multiple resource constraints past the first period.[68] An alternate method of accounting for the multistage aspect is the representation of R&D projects in a decision or project tree format that is used to develop the constraint equations for linear or integer programming algorithms. The major work in this area is by Gear and Lockett;[69] Hespos;[70] Gear, Gillespie and Allen;[71] and Flinn and Turbin.[72] Project trees, as developed by Hespos, are used to represent the evolution of projects or project versions, resource requirements, and any associated uncertainties over the planning horizon, thus enabling each project version to be diagramatically planned on a common time scale. As part of the research reported in Chapter III, project tree planning is described in conjunction with the multiple objective, zero-one goal programming model, presented.

Multicriteria Models

None of the models surveyed explicitly address a multiple criteria objective function with noncommensurate goals for the dynamic case, although several models indirectly approach the problem. Dean and Roepcke's cost effectiveness model[73] includes a weighted value coefficient for each task (project) included in the objective function. The values are determined by developing a list of independent multiple objectives. Tasks are rated against each of the objectives and a final weighted value is determined by summation. Nutt,[74] Adams,[75] and Chiu and Gear[76] use similar concepts in arriving at dimensionless coefficients for projects included in the mathematical programming objective function. In these approaches, a portfolio of projects is developed, however it is not possible to directly determine the achievement level of the various objectives through an analysis of model results. Furthermore, a project rated high on lower priority objectives but low on the highest priority goal could drive this project into solution while failing to attain the highest priority goal.

Rosen and Souder[77] recognized the multiple objective nature of the project selection decision and considered four objectives in their model by using an objective ordering technique. Projects are selected by maximizing expected profits. The solution is then checked to determine achievement of three additional objectives: maximizing total expected output (expected research successes), achieving a specified return on expenditures, and achieving a predetermined success level for a specific project. If any of these additional objectives are not achieved, the problem is rerun by dropping out low expected profit projects, relaxing the objectives, or changing the constraints.

Although the Charnes and Stedry[78] model was concerned with allocating funds over various research areas and not with project selection, it is reviewed here as multiple goals are considered. The model, which is based on chance-constrained programming, minimizes a variety of expected activity costs subject to ensuring that short-run and long-run research activity levels or goals are met. Chance constraints are used to ensure that, within a given probability, resource availabilities are not exceeded in meeting the activity levels.

Utility theory has also been suggested as a means of incorporating multiple objectives (see for example Watters[79] and Keefer[80]). For the selection problem, the decision maker's objective is to maximize the expected utility of the portfolio's multidimensional return function. The method of determining the utility function is extremely difficult to handle from a practical standpoint, even for just four dimensions, since subjective questioning is required to discover indifference levels between alternative options presented to the decision maker.[81] In addition, Lee's research[82] noted that under normal circumstances it is very difficult for decision makers to measure precisely how much more important one goal is to another in the cardinal values used in utility theory.

In a recent publication, Muhlemann, Lockett and Gear[83] extend previous work done on project tree and mathematical program modeling to the multiple objective case. While their method is applicable for those problems in which the goals are measured in common dimensions, it is not designed for the more realistic, noncommensurate multicriteria case. Keown, Taylor and Duncan[84] have also suggested the application of integer goal programming for the multiple criteria selection problem. Although their technique approporiately addresses noncommensurate multiple objectives ranked on an ordinal scale, it is limited to the static case and to small scale problems.

Model Prescriptions

A number of representative models have been identified which possess some of the many features a general project selection/resource allocation model should have. From this review a set of prescriptions can be developed for a model that can be used as an analytic technique in the larger R&D decision making process. In summary form, the project selection/resource allocation model should be capable of:

1) Selecting a set of research and development projects that are chosen to maximize the attainment of multiple objectives.
2) Incorporating the multistage and sequential decision making nature of R&D projects.
3) Addressing the limitations of scarce multiple resource constraints.
4) Representing mutually exclusive projects or versions.
5) Incorporating discrete probability estimates or probability distributions for the various parameter estimates, and be capable of considering estimate error.
6) Representing the interaction and interrelationships of projects.
7) Representing any balance required in the R&D program such

as between basic research and development work.

8) Considering experience and knowledge of R&D personnel and interacting with these personnel in the larger R&D decision making system.

9) Including some type of sensitivity analysis capability to consider the "what if" type questions associated with the uncertain R&D selection/allocation problem environment.

10) Generating solutions to realistic size problems.

The model presented in the following chapter, which represents the major focus of this research, has been designed with these prescriptions in mind.

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CHAPTER III

THE MULTISTAGE ZERO-ONE GOAL PROGRAMMING MODEL

This chapter presents the zero-one goal programming R&D project selection model, including techniques for incorporating the multistage nature of R&D projects and stochastic parameters. The first section includes a discussion of goal programming concepts, formulations and existing solution techniques. Next, project decision tree planning is described as a means of representing the evolution of projects over the multiperiod planning horizon. The following two sections incorporate project tree planning techniques into goal programming model formulations. The solution algorithm is presented, illustrated and tested in the final sections of this chapter.

Goal Programming Concepts and Formulation

The R&D project selection and resource allocation decision is made in an environment where projects should be selected and evaluated against multiple criteria having no common underlying measure.[1] These multiple criteria are not necessarily of equal importance to the organization and various ranking schemes have been suggested to reflect this hierarchy of importance.[2]

The discussion in the preceding chapter indicated a number of reasons why the project selection techniques which have heretofore been discussed in the literature are inadequate in addressing the full complexities of the selection problem. Hence, another approach seems necessary. Linear goal programming, first developed by Charnes and Cooper[3] and later refined by Ijiri,[4] Lee,[5] and Ignizio,[6] provides a partial solution to some of the deficiencies noted above; namely its ability to deal with problem formulations having ordinally ranked, noncommensurate multiple objectives.[7] The technique has been applied to related decision areas such as selection of capital investment projects,[8] and resource allocation in nonprofit institutions,[9] and is proposed for the R&D project selection/resource allocation problem.

The basic concept of goal programming involves the incorporation of the multiple objectives, pertinent to the problem being considered, into a model by setting quantified levels of achievement or goals for each of the objectives.[10] Primary goals, which may be noncommensurate in their units of measurement, are ranked on an ordinal scale to reflect their relative importance to the model users. Preemptive priority levels are assigned to each goal to preserve the ordinal ranking, thus assuring that more important goals are achieved before attempts are made to attain goals of lesser importance. It is important to note that goal programming also allows for a cardinal ranking of primary goals having common units of measurement and for a cardinal ranking of any subgoals of a primary goal. The objective in goal programming is to seek out that solution which comes as close as possible to satisfying all of the quantified goals. This is accomplished by minimizing the over- or underattainment of the goals based upon their relative importance.[11] Over- or underattainment of goals is represented by deviational variables in system and goal constraint equations, where system constraints define the relationships among the decision variables, and goal constraints define the relationships between the decision variables and the goals.[12] These deviational variables are expressed in two dimensions: p_i represents positive deviation from an established goal i and n_i represents negative deviation. The general linear goal programming model, as presented by Ignizio,[13] is:

Find $\bar{x} = (x_1, \ldots, x_j)$ so as to minimize (3.1)

$$\bar{a} = \left\{ P_1[g_1(\bar{n}, \bar{p}], \ldots, P_k[g_k(\bar{n}, \bar{p}] \right\} \tag{3.2}$$

such that:

$$f_i(\bar{x}) + n_i - p_i = b_i \qquad i = 1, \ldots, m., \tag{3.3}$$

and $\bar{x}, \bar{n}, \bar{p} \geq 0$

where: $\bar{x}$ is the vector of decision variables (i.e., selected projects).

(3.2) is the achievement function where the dimension of $\bar{a}$ represents the number of preemptive priorities among the objectives.

P_k is the priority level of $g_k(\bar{n}, \bar{p})$.[14]

$g_k(\bar{n}, \bar{p})$ is a linear function of the deviational variables, which may be cardinally ranked.

$K \leq m$ where m is the number of objectives.

(3.3) are the problem objective equations.

$f_i(\bar{x})$ is a function of the decision variables associated with the ith constraint.

b_i are the quantified goals for the objectives.

In formulating the project selection problem as a linear goal program, the decision variables, x_j, representing projects to be selected for the portfolio, would be further constrained by an upper bound of one to preclude duplicate projects being accepted.

Algorithms for solving the linear goal programming model include the general inverse method developed by Ijiri[15] and the more efficient modified simplex method introduced by Lee.[16] Research endeavors utilizing the linear goal programming formulations and solution methods must accept the divisability requirements placed upon the decision variables as is true with linear programming. In the previous chapter it was pointed out that linear programming algorithms used to solve the project selection problem can lead to portfolios with fractional projects. Since fractional projects lead to interpretation difficulties, and since a rounded-off solution is generally either infeasible or not optimal for the problem being solved, an integer algorithm is necessary to meet the zero-one restrictions on the x_j variables.

In a recent Ph.D. dissertation, Morris[17] adopted cutting plane, branch and bound and implicit enumeration techniques in developing algorithms for integer goal program formulations. The implicit enumeration technique was specifically designed for the zero-one problem and is based on the additive algorithm of Balas,[18] as modified by Glover.[19] The technique works by enumerating all project selection combinations represented by the vector $\bar{x}$, either explicitly or implicitly. Certain solutions are evaluated and then logic is used to eliminate further solutions without evaluating them explicitly. Initial solutions are created by systematically adding free variables (variables not yet assigned a value of zero or one) to $\bar{x}$ to determine if goal attainment for the highest, unachieved priority goal can be improved.[20] When no further improvement is possible, a backtracking routine is initiated by removing the last decision variable assigned to the most current solution. From this modified solution, additional solutions are created by systematically adding remaining free variables to $\bar{x}$ to determine if goal attainment levels can be further improved. The entire process is repeated until all solution combinations have been explicitly or implicitly evaluated. Even though the algorithm is designed to minimize the number of solutions that must be explicitly evaluated, large scale problems require many evaluations. For this reason, the algorithm is limited to problems with an upper bound of approximately 20 variables, 50 constraints and 10 priority levels.

Since the integer goal program formulation, with the associated implicit enumeration solution technique, addresses an important aspect of the R&D project selection problem, the existence of multiple objectives having no common underlying measure, it will form the starting point for the development of a method of performing R&D project selection in realistic situations. However, while the implicit enumeration algorithm is limited to applications involving no more than 20 project proposals, interviews conducted during the course of the present research indicated that practical applications involve at least 20 to 40 project proposals (see also Souder[21] and Lockett and Gear[22]). For instance, managers of the research and development laboratories of the textile firm and the phamaceutical company interviewed, report that approximately 30 to 40 ongoing and new projects comprise the set of projects under evaluation at semicontinuous time periods. Therefore, to be useful, it is necessary to design an algorithm capable of solving at least these medium size problems. In the present research, a zero-one goal programming algorithm is developed to achieve this capability.

Zero-One Goal Programming Algorithm

The principal objective of this research is to develop a zero-one goal programming algorithm for solving R&D project selection problems of realistic size. A subgoal of this objective is to generate good working solutions within a relatively small computation time. Since the model is proposed as an interactive decision aiding tool, it is envisioned that model users would benefit from having a range of solutions for qualitative assessment. Further, if stochastic parameters are considered and simulation techniques are used for sampling their probability distributions, many model runs are required for statistical hypothesis testing. Thus, even though the Morris algorithm provides exact solutions for problems with up to 20 variables, the relatively long computation time for upper range problems makes multiple runs expensive. For example, Morris reported that a 19 variable test problem required over 15 minutes of computation time on an IBM 370/158 system.[23] If just 30 runs were desired for sensitivity analysis or hypothesis testing, the cost and time may be prohibitively high. The proposed algorithm is based on heuristic techniques and it is recognized that one of the disadvantages of heuristics could occur during the sensitivity analysis stage; that is, a range of solution strategies close to the exact solution may be influenced by both the changes to input data and the vagrancies of the heuristic procedure.[24] The counter argument for heuristics concerns the practical aspect of obtaining good solutions to medium size problems unsolvable with existing techniques, and with the further advantages of speed and versatility.[25]

Before describing the solution algorithm, the following terms are defined:

V_1 = The set of indices of all unassigned or free project variables x_j, that is, those x_j not yet assigned a value of zero or one.

V_2 = The set of indices of all project variables in solution, that is, those $x_j = 1$.

V_3 = The set of indices of all project variables forced out of the solution, that is, those $x_j = 0$.

U = The set of goal underachievements at the various priority levels. If U_i is attained, $U_i = 0$.

U^* = The upper bound, or best solution determined so far during the variable selection routine. The variables in V_2 and V_3 which generate U^* are recorded as V_2^* and V_3^*.

U^{**} = The upper bound or best solution determined so far during one iteration of the variable exchange routine. The variables in V_2 and V_3 associated with U^{**} are recorded as V_2^{**} and V_3^{**}.

U^{***} = The minimum or best solution among the U^{**} solutions determined during the variable exchange routines. The variables in V_2 and V_3 associated with the solution U^{***} are recorded as V_2^{***} and V_3^{***}.

The procedure begins with a one pass variable selection routine adapted from Morris[26] that rapidly builds an initial solution. During the initialization step, all x_j are set equal to zero but considered as free variables so that $V_2=V_3=\emptyset$, and U is computed and designated as U^* to indicate the upper bound or best solution so far. Next, each variable in V_1 is considered individually as a solution variable for inclusion in

V_2 and that one which results in the greatest improvement to U^* is selected. That variable is removed from V_1 and added to V_2 , and U^* is changed. This process continues iteratively until no further reduction in the goal underattainment levels is possible. It is noted that during this routine, if a variable under consideration does not improve U^*, it is added to V_3. When $V_1=\emptyset$, the procedure terminates and U^* with the associated V_2^* and V_3^* vectors are recorded. Further, U^{***}, V_2^{***} and V_3^{***} are initialized at U^*, V_2^*, and V_3^*, respectively, and saved for use later on in the algorithm.

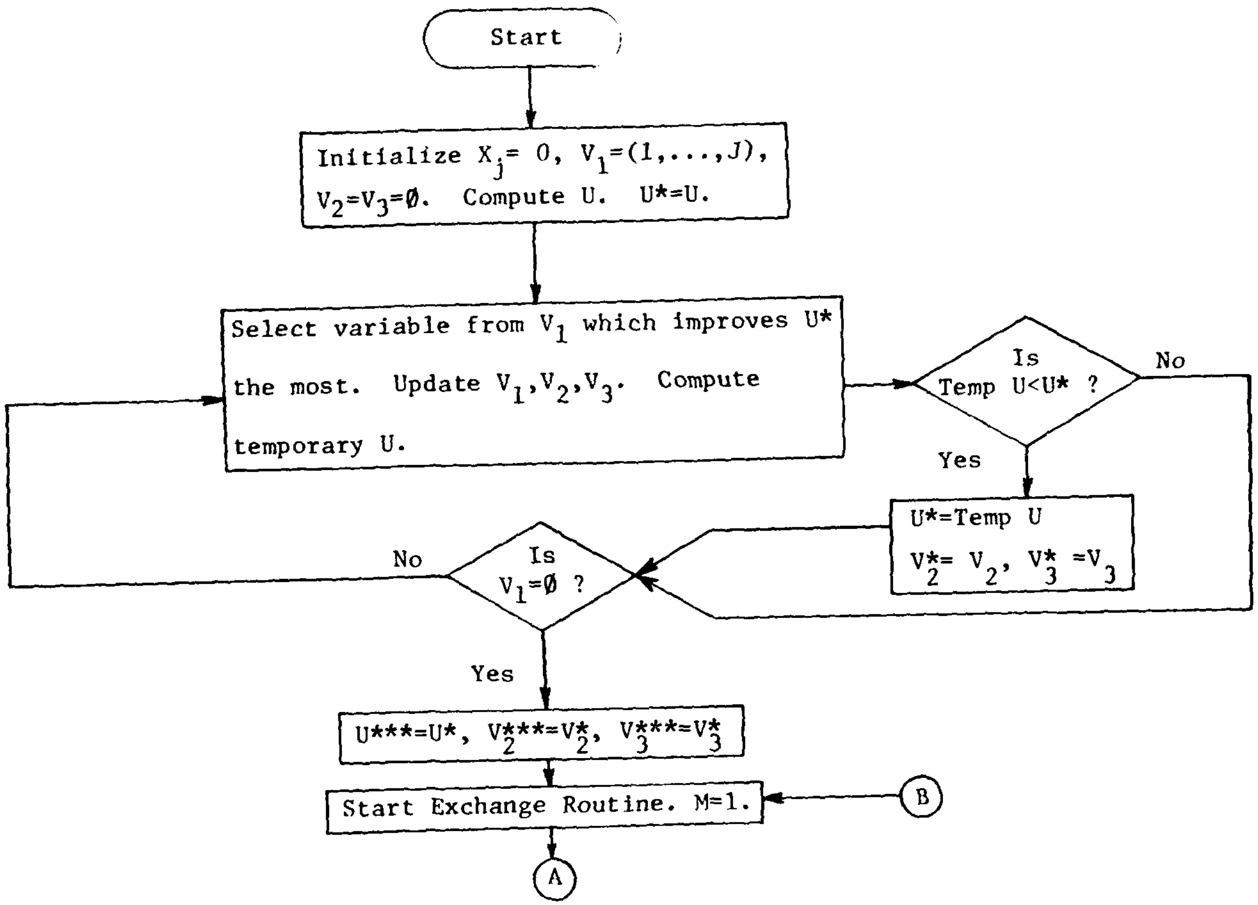
The next procedure is a one-by-one variable exchange routine that iteratively operates on the set V_2^*. The procedure begins by transferring all variables from V_3^* to V_1 so that $V_3=\emptyset$. Then, the variable with the smallest index is removed from V_2^* and added to V_3. U is computed and recorded as U^{**} and the variable selection routine starts again, this time attempting to find solutions that improve on U^{**}. If any U computed during this stage is also less than U^*, the solution is tested against U^{***} to determine if a global improvement is possible. If so, U^{***} and the associated V_2^{***} and V_3^{***} vectors are changed to record this solution as the best found so far. The procedure continues until $V_1=\emptyset$. At this time, the variable that was removed from V_2^* is replaced in V_2^* and the variable having the next largest index is removed for the next iteration of the variable selection routine. The procedure continues until all variables in the set V_2^* have been exchanged. If there was an improvement to U^{***} during any of the exchange iterations, the entire exchange routine starts again with $U^*=U^{***}$, $V_2^*=V_2^{***}$, and $V_3^*=V_3^{***}$. The procedure terminates when no further improvement to U^{***} can be found. A flow chart illustrating this procedure is shown in Figure 3-1 on pages 44 and 45.

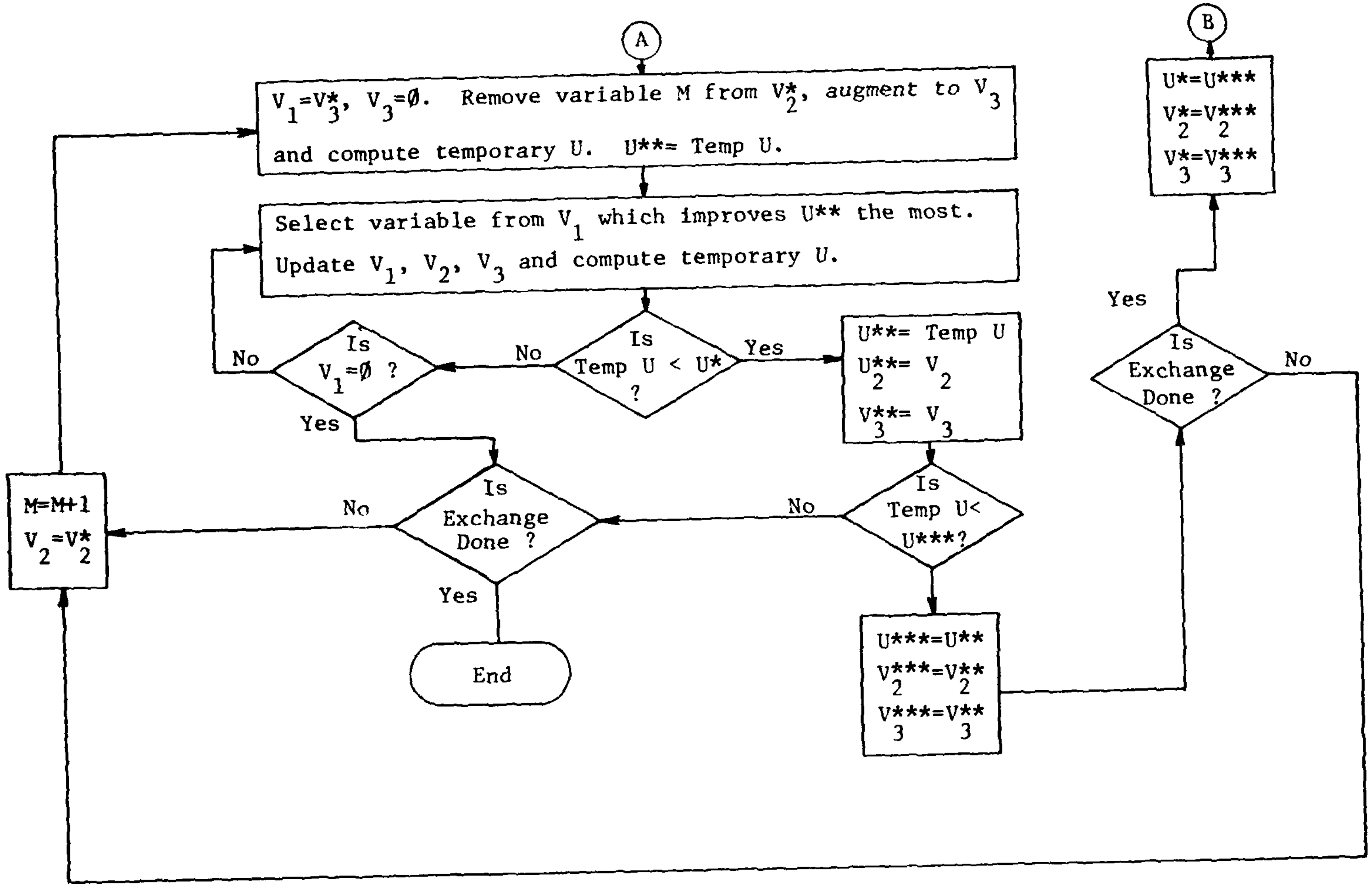
It is noted that the exchange routine described above is somewhat related to the general class of interchange heuristics employed as solution algorithms for zero-one, single objective programming problems. For example, in the warehouse location problem, Kuehn and Hamburger[27] use a "bump and shift" heuristic to close one or more warehouses that were selected to be opened by an additive main program heuristic and to open other warehouses that were not selected for opening in the main program, in attempts to make improvements in the evaluation criterion (minimize distribution system costs). For another example, Cornuejols, Fisher and Nemhauser[28] describe a pairwise interchange heuristic for the bank account location problem where, given an initial solution of locations for bank accounts, attempts to improve the evaluation criterion (maximize check clearing times) are made by exchanging one selected bank location for another not yet selected. The particular entering-leaving pair is selected in a variety of ways, for example, first improvement or maximum improvement.

Project Trees

Descriptive studies cited in Chapter II note that to be useful, R&D project selection and resource allocation models should account for the multistage, sequential nature of projects and the uncertainty that exists in project evolution and resource parameters. As is, the Morris integer goal programming formulation does not do this. The use of project trees in combination with a mathematical programming technique and simulation or with stochastic programming techniques are methods of incorporating this dynamic nature and uncertainty into the goal programming format, and this further improve our ability to address the

Figure 3-1
Solution Procedure Flow Chart




A
V1=V*3, V3=∅. Remove variable M from V*2, augment to V3 and compute temporary U. U**= Temp U.
Select variable from V1 which improves U** the most.
Update V1, V2, V3 and compute temporary U.
Is Temp U < U* ?
Yes
No
U**= Temp U
U**2= V2
V**3= V3
Is V1=∅ ?
No
Yes
Is Temp U< U***?
No
U***=U**
V***2=V**2
V***3=V**3
Is Exchange Done ?
No
Yes
End
M=M+1
V2=V*2
Is Exchange Done ?
Yes
No
U*=U***
V*2=V***2
V*3=V***3
B

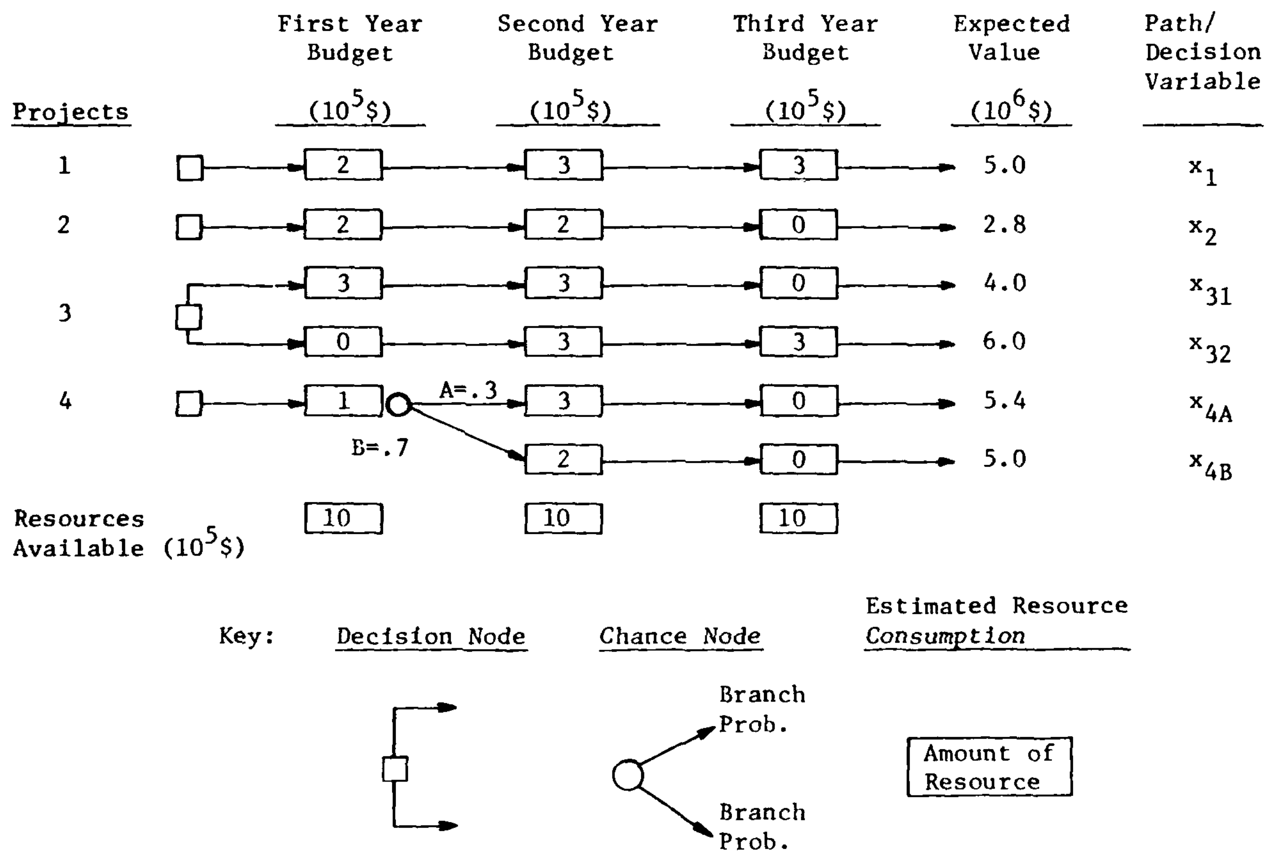
inadequacies of the model discussed in the review of the literature (Chapter II).

The project tree structure is a promising means of analysis as it can be used to represent many of the aspects of the R&D project selection environment. In addition to incorporating the multistage nature of R&D projects, the representation allows for:

1) The examination of the relative merits of series or parallel strategies (see for example, Abernathy and Rosenbloom[29]).
2) The analysis of various start delays and rates of resource usage.
3) The representation of uncertainties in project duration, resource requirements, project outcomes and project values.
4) The inclusion of a mixture of applied research, basic research and development projects.
5) The representation of mutually exclusive or dependent projects.

The project trees in Figure 3-2 follow the format presented by Gear and Lockett[30] and are included to illustrate some of the features listed above. In this figure, projects 1 and 2 have deterministic technical outcome paths but reflect different resource consumption patterns, time durations and expected outcome values. Project 3 can be performed in either of two mutually exclusive versions, x_{31} or x_{32}, the second of which has a one year start delay and a higher expected value when compared to the first version. Project 4 has a period of research followed by a chance node reflecting an uncertain technical outcome with two future events that would dictate different funding levels in the second year and result in different expected values depending upon

Figure 3-2
Illustrative Project Trees



whether chance branch A or chance branch B occurs. The resource allocation problem is thus stated as: what subset of projects should resources be allocated to in order to be on an optimal path in terms of maximizing the sum of terminal values for projects eventually completed?[31]

By using project trees in the manner described, the multiperiod nature of R&D projects can be explicitly recognized and appreciated in the project selection decision.

Consideration of the Stochastic Nature of R&D Project Selection

The high risk and uncertainty which characterize R&D limit the utility of project selection models which are confined to deterministic representations of the problem. Accordingly, simulation or stochastic programming has been suggested to incorporate the stochastic parameters and chance future events from the project tree diagram for the single objective problem.[32] This research extends these techniques to the multiple noncommensurate objective case with discrete project variables.

To illustrate the stochastic formulation of the integer goal program, the R&D project selection problem already presented in the Figure 3-2 project tree description will be used for an example. Let the first priority goal be to require the inclusion of project 3 in the research portfolio. This goal is representative of realistic situations in which the R&D manager must include specifically identified project proposals in the research effort, where such identification normally comes from higher organizational levels. For example, one proposal may represent a defense project which, by itself, has a low return to the firm and would not normally be selected, but is expected to generate a large follow-on contract business.[33] In this case, top management may intervene in the selection process and request this project be funded. The second priority goal is not to exceed the budget levels in each of the three time periods, and the third priority goal is to maximize the expected value of the portfolio selected.

The constraint equations for the stochastic goal programming formulation are shown in Table 3-1. The first goal is achieved by minimizing n_1 and p_2 in rows 1 and 2 of the table.[34] The second goal is satisfied by minimizing the positive deviational variables in rows 3 through 6. Row 3 represents the first period budget constraint goal; rows 4 and 5 represent the second period budget goal, one row for each possible future outcome of project 4; and row 6 represents this goal in the third period. The third goal is achieved by minimizing n_7 from a large, unattainable right hand side value. All technological coefficients in the constraint equations are obtained directly from Figure 3-2 except the expected value for project 4. The expected value of project 4 is the probability of chance branch A times the expected value of x_{4A} plus the probability of chance branch B times the expected value of x_{4B}:

$$\text{Expected Value Project 4} = (.3)(5.4) + (.7)(5.0) = 5.12 \qquad (3.4)$$

Table 3-1
Model Constraints for Example Problem

Row No.	X_1	X_2	X_{31}	X_{32}	X_4	n_i	p_i	Sign	RHS
1			1	1		n_1	$-p_1$	=	1
2			1	1		n_2	$-p_2$	=	1
3^a	2	2	3		1	n_3	$-p_3$	=	10
4^a	3	2	3	3	3	n_4	$-p_4$	=	10
5^a	3	2	3	3	2	n_5	$-p_5$	=	10
6^a	3			3		n_6	$-p_6$	=	10
7^b	5	2.8	4	6	5.12	n_7	$-p_7$	=	25

(Variables: X_1 through p_i)

$^a(10^5\ \$)$; $^b(10^6\ \$)$

The integer goal programming formulation also requires x_j=0,1 and n_i, $p_i \geq 0$ for all j project variables and i deviational variables. The objective function is:

$$\text{Minimize } \bar{a} = \left[P_1(n_1+p_2);\ P_2(p_3+p_4+p_5+p_6);\ P_3(n_7) \right] \qquad (3.5)$$

The disadvantage of the stochastic programming approach described above is that with many chance future events, the constraint set becomes unmanageable. For example, Lockett and Gear[35] examined an industrial case with 37 projects, 65 decision nodes and 40 chance nodes involving four time periods and six resource categories. They reported that the size of the problem prohibited the application of stochastic linear programming as the number of constraints ran into millions. Obviously, this is also a disadvantage of the stochastic zero-one goal programming formulation. Another disadvantage of the stochastic linear or goal programming approaches is that the solution represents the best portfolio strategy for all possible future events, without recognizing that the occurrence of some of these events could be highly unlikely.

One alternative solution technique is simulation where each chance node is sampled by Monte Carlo processes to determine which path and associated path variable from the project trees is to be input into the mathematical program.[36] Chance nodes are repeatedly sampled and the results of associated mathematical programs are recorded. In a large problem, it can be expected that many portfolios will be generated for the simulated possible outcomes. These portfolios can then be subjected to statistical analysis in order to compare the stability, objective values and frequency of portfolio occurrences.

Another simulation technique, which utilizes the model as a truely effective interactive device, is suggested when several of the many chance future events are clearly dominant or otherwise of interest to the decision makers. In this case, the model users would predetermine the occurrence of these future events and provide the associated path variables as input data for the model; and receive, as output, the suggested portfolio strategy and associated goal attainment levels for further statistical or subjective analysis. In this manner, the model users are able to evaluate strategies associated with specific or dominant future events in contrast with the stochastic approach which recognizes the existence of all future events, including those that are highly unlikely.

Table 3-2
Model Constraints for Example Problem

Variables

Row No.	X_1	X_2	X_{31}	X_{32}	X_{4B}	n_i	p_i	Sign	RHS
1			1	1		n_1	$-p_1$	=	1
2			1	1		n_2	$-p_2$	=	1
3^a	2	2	3		1	n_3	$-p_3$	=	10
4^a	3	2	3	3	2	n_4	$-p_4$	=	10
5^a	3			3		n_5	$-p_5$	=	10
6^b	5	2.8	4	6	5	n_6	$-p_6$	=	25

$^a(10^5\ \$)$; $^b(10^6\ \$)$

To illustrate the zero-one goal programming formulation with simulation technique, the example problem described in Figure 3-2 will be used. For this illustration, the model users are interested in the portfolio strategy suggested if dominant branch B of the project tree shown in Figure 3-2 occurs. The model constraints are provided in Table 3-2 above and the objective function is:

$$\text{Minimize } \bar{a} = \left[P_1(n_1+p_2);\ P_2(p_3+p_4+p_5);\ P_3(n_6) \right] \tag{3.6}$$

Solutions to this and the stochastic zero-one goal programming formulations will be presented in the next section.

An Illustration of the Solution Algorithm

To illustrate the variable selection and exchange heuristic proced ɜ, the example R&D project selection problem shown in the project trees of Figure 3-2 is presented. The stochastic zero-one goal programming formulation previously described and shown in Table 3-1 will be used in this illustration.

Step 1: The first step is to set all variables equal to zero and obtain an initial solution:

$V_1 = (1,2,31,32,4)$

$V_2 = \emptyset$

$V_3 = \emptyset$

$U^* = U = (1,0,25)$

Step 2: Next, that variable which will improve U^* to the greatest extent is selected for solution. Underachievement exists at the first priority level, and involves the negative deviational variable n_1. Consequently, the variable with the largest positive coefficient in row 1 is chosen for solution. In this case, there is a tie between x_{31} and x_{32} which is broken by arbitrarily selecting the variable with the smallest index number, x_{31}. In the computer program, if one priority level has more than one row with negative deviational variables, the sum of the coefficients over these rows is computed for each respective variable to determine the largest sum. It can be seen, then, that to minimize goals of negative deviations, variables are selected that have large coefficients. The results at the end of this step are:

$V_1 = (1,2,32,4)$

$V_2 = (31)$

$V_3 = \emptyset$

$U^* = U = (0,0,21)$

Step 3: The first two goals are completely satisfied but the third is underattained. The third goal involves minimization of the negative deviation in row 7 so the variable from V_1 with the largest coefficient in row 7 is added to V_2, provided that this selection does not result in an increase in the underattainment of the higher priority goals. For example, x_{32} has the largest coefficient of the variables in row 7 of Table 3-1, but its selection would result in U = (1,0,15) which is not less than U^*. Therefore, $V_3 = (32)$ and the variable with the next largest coefficient is examined. The results at the end of this step are:

$V_1 = (1,2)$

$V_2 = (31,4)$

$V_3 = (32)$

$U^* = U = (0,0,15.88)$

Step 4:

$V_1 = (2)$

$V_2 = (31,4,1)$

$V_3 = (32)$

$U^* = U = (0,0,10.88)$

Step 5:

$V_1 = \emptyset$

$V_2 = (31,4,1)$

$V_3 = (32,2)$

$U^* = U = (0,0,10.88)$

Since $V_1 = \emptyset$, the variable selection routine is completed and

$U^{***} = (0,0,10.88)$, $V_2^{***} = (31,4,1)$, and $V_3^{***} = (32,2)$. The exchange procedure is not initiated.

Step 6: (Exchange variable x_1)

$V_1 = (32,2)$

$V_2 = (31,4)$

$V_3 = (1)$

$U^{**} = U = (0,0,15.88)$

Step 7: (Begin the variable selection routine)

$V_1 = (32)$

$V_2 = (31,4,2)$

$V_3 = (1)$

$U^{**} = U = (0,0,13.08)$

Step 8:

$V_1 = \emptyset$

$V_2 = (31,4,2)$

$V_3 = (1,32)$

$U^{**} = U = (0,0,13.08)$ (End the variable selection routine)

Step 9: (Exchange variable x_{31})

$V_1 = (32,2)$

$V_2 = (4,1)$

$V_3 = (31)$

$U^{**} = U = (1,0,14.88)$

Step 10: (Begin the variable selection routine)

$V_1 = (2)$

$V_2 = (4,1,32)$

$V_3 = (31)$

$U = (0,0,8.83)$. Since U is less than U^*, U^{**}, and U^{***}:

$U^{**} = U^{***} = (0,0,8.38)$

$V_2^{**} = V_2^{***} = (4,1,32)$

$V_3^{**} = V_3^{***} = (31)$

<u>Step 11</u>:

$V_1 = \emptyset$

$V_2 = (4,1,32)$

$V_3 = (2,31)$

$U = (0,0,8.88)$ (End the variable selection routine.)

The variable exchange routine is repeated once more, with x_4 forced out of the solution, thus completing the exchange of all the variables in V_2 at the end of step 5. The best solution during the three exchange iterations was determined to be $U^{***} = (0,0,8.88)$ and $V_2^{***} = (1,32,4)$. The variable exchange heuristic is then repeated with this solution set and no further improvement was found in the nine additional steps. Note that while the problem was solved in 20 steps, some of the steps are for record keeping and the actual number of iterations involving the evaluation of solution combinations was 10, which is about one third of the possible 32 solution combinations (2^5). The best solution, which is also optimal, then is to select projects 1 and 4 and version 2 of project 3. The first two goals are attained and the expected benefit for the third goal is \$ 16,120,000 (\$ 25,000,000 - \$ 8,880,000).

In conclusion, it is important to note that the stochastic formulation and resultant solution provides the optimal strategy for both possible future events, without recognizing that the occurrence of event A is unlikely. If the problem is resolved considering only the dominant future event B, the solution is to select projects 1, 2, version 2 of project 3, and project 4 with a resultant expected benefit of $ 18,800,000. *This solution is for the zero-one goal programming* formulation with simulation techniques as was described in Table 3-2. Dominant future event analysis is discussed in greater detail in Chapter IV.

Results of Testing the Heuristics Against the Morris Algorithm

The variable selection and exchange heuristic procedures presented here were tested on six problems which are described in Table 3-3. Problems 1 and 4 through 6 are from Morris[3/] and problems 2 and 3 were created to test additional problem structures. Computer program runs were performed on an IBM 370/155 system, except where indicated, and CPU time reported is for computation and printing the final solution. The results for the one-by-one exchange heuristic reflect substantial time reductions while reaching the optimal solutions for four of the six problems. Analysis of the two solutions where optimality was not achieved indicate that the procedure was locked into local minima on the multidimensional goal attainment response surface. Accordingly, a partition procedure was added to the algorithm so that several forced subproblems are created and solved. The solution with the best goal attainment levels (Minimum U^{***}) is selected as the solution to the original problem. The partition procedure was designed for the particular structure of the R&D project selection problem where it is often the case that one or more projects are proposed in mutually exclusive project versions, thereby generating system constraints of

Table 3-3
Zero-One Model Comparisons

Problem Description	Problem 1	Problem 2	Problem 3	Problem 4	Problem 5	Problem 6
Variables (n)	10	10	12	14	17	19
Constraints	15	15	19	17	14	25
Priorities	6	6	8	7	5	10
Soln Combinations (2^n-1)	1023	1023	4095	16384	131072	524288
Morris Algorithm						
Iterations	373	373	1569	1104[a]	34554[a]	19855[a]
CPU (Seconds)	3.5	3.5	18.8	25	574	919
Optimal Solution	Yes	Yes	Yes	Yes	Yes	Yes
Exchange Heuristic						
Iterations	13	22	27	9	28	63
CPU (Seconds)	.5	.5	.8	.8	.9	3.6
Optimal Solution	Yes	Yes	Yes	No	Yes	No
Partition Plus Exchange Heuristic						
Nbr of Subproblems	2	2	6	14	10	17
Iterations	29	29	135	144	230	908
CPU (Seconds)	.6	.6	2.3	2.4	3.4	46.4
Optimal Solution	Yes	Yes	Yes	Yes	Yes	Yes

[a]Runs made on IBM 370/158

the type illustrated below:

$$x_{11} + x_{12} \leq 1. \tag{3.7}$$

This equation is transformed into a goal programming format as follows:

$$x_{11} + x_{12} + n_1 - p_1 = 1, \tag{3.8}$$

and the objective is to minimize p_1 at the first priority level which guarantees solution feasibility. For this equation, two artificial problems can be created; one with x_{11} forced out of the solution and the other with x_{12} forced out. The procedure is performed by holding the selected variable in the set of projects forced out of the solution (V_3) during the variable selection and exchange operations.

While the partition technique was designed for the particular structure of the R&D project selection problem, the procedure is general and may be applied to problems not having mutually exclusive system constraints. For medium size problems with up to 45 project variables, full partitioning may be efficiently employed by creating one subproblem for each project variable. For larger problems, selective partitioning may be effectively used by first running the model with only the variable selection and exchange heuristics and then rerunning the model by partitioning on the variables in solution.

The model results for the partition procedure combined with the variable selection and exchange heuristics are also shown in Table 3-3. For problems 1, 2, 3, 5 and 6, partitioning was performed on the mutually exclusive project versions. For problem 4, full partitioning was used due to the absence of mutually exclusive system constraints. As these results indicate, improved solutions may be obtained by using the partitioning procedure. The reason for this is due to the operation of the exchange procedure, which interchanges one solution variable with one or more variables not yet in the solution at each iteration. Other procedures such as exchanging two or three solution variables with one or more variables not yet in the solution could increase the chance of reaching the global minimum but only at the expense of increased model complexity and computation time. The partition procedure is a simple alternative and is shown to be efficient in tests of the algorithm.

A user's guide for the associated computer program is provided in Appendix A.[38] This guide includes a description of the computer code, data card preparation instructions, and suggestions for using the three options of the code which are summarized as follows:

1) Option 1: This option employs the variable selection heuristic without the exchange procedure.

2) Option 2: This option incorporates both the variable selection and exchange procedure as previously described in this chapter.

3) Partitioning Option: The partitioning procedure may be used with either option 1 or 2 above.

The computer code with sample output is provided in Appendix B.

Footnotes

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[12]________________________, "Multicriteria School Busing Models," Management Science, Vol. 23 (March, 1977), pp. 703-715.

[13]Ignizio, p. 17.

[14]A more efficient form of equation (3.2) is achieved by dropping out the preemptive priority factors P_k which only serve to signify that $g_1(\bar{n},\bar{p})$ is minimized first, then $g_2(\bar{n},\bar{p})$, and so forth. $P_k g_k(\bar{n},\bar{p})$ does not imply that P_k is multipled times $g_k(\bar{n},\bar{p})$, nor that P_k is a function of $g_k(\bar{n},\bar{p})$.

[15]Ijiri.

[16]S. M. Lee, "Decision Analysis Through Goal Programming," Decision Sciences, Vol. 2 (April, 1971), pp. 172-180.

[17]Morris.

[18]E. Balas, "An Additive Algorithm for Solving Linear Programs with Zero-One Variables," Operations Research, Vol. 13 (September-October, 1965), pp. 517-545.

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[20]The algorithm begins with an initial solution for all project variables equal to zero.

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[32]Ibid.

[33]E. B. Roberts, and W. H. Dyer III, "Follow-On Contracts in Government-Sponsored Research and Development: Their Predictability and Impact," Industrial Management Review, Vol. 9 (Winter, 1968), pp. 41-55.

[34]The solution procedure is designed to minimize one deviational variable for each goal constraint equation. For an equality constraint where both the negative and positive deviational variables are to be minimized, two constraints are therefore required.

[35]Lockett and Gear, "Representation and Analysis of Multistage Problems in R&D."

[36]Ibid.

[37]Morris, Chapters VI and VII.

[38]The data input format follows closely that of the Morris implicit enumeration code (Morris, pp. 129-131) so that with minor changes the heuristic solution may be checked against the optimal solution for small scale problems.

CHAPTER IV

R&D PROJECT SELECTION CASE STUDY

This chapter presents a hypothetical R&D project selection case study to provide a comprehensive demonstration of the zero-one goal programming model. The project selection problem is first described in the project tree format discussed in Chapter III. Methods for modeling the more complex aspects of parallel versus series research strategies and dependent project interrelationships are included. Next, organizational objectives are developed and the goal programming model is formulated using information from the project trees. Two experiments are then described, the first of which concerns analysis of research strategies associated with various future technical outcome events of interest to the model users. The second experiment involves sensitivity analysis on the multiple objective priority structure. The chapter concludes with a discussion of an alternate method of using the model for determination of the research portfolio.

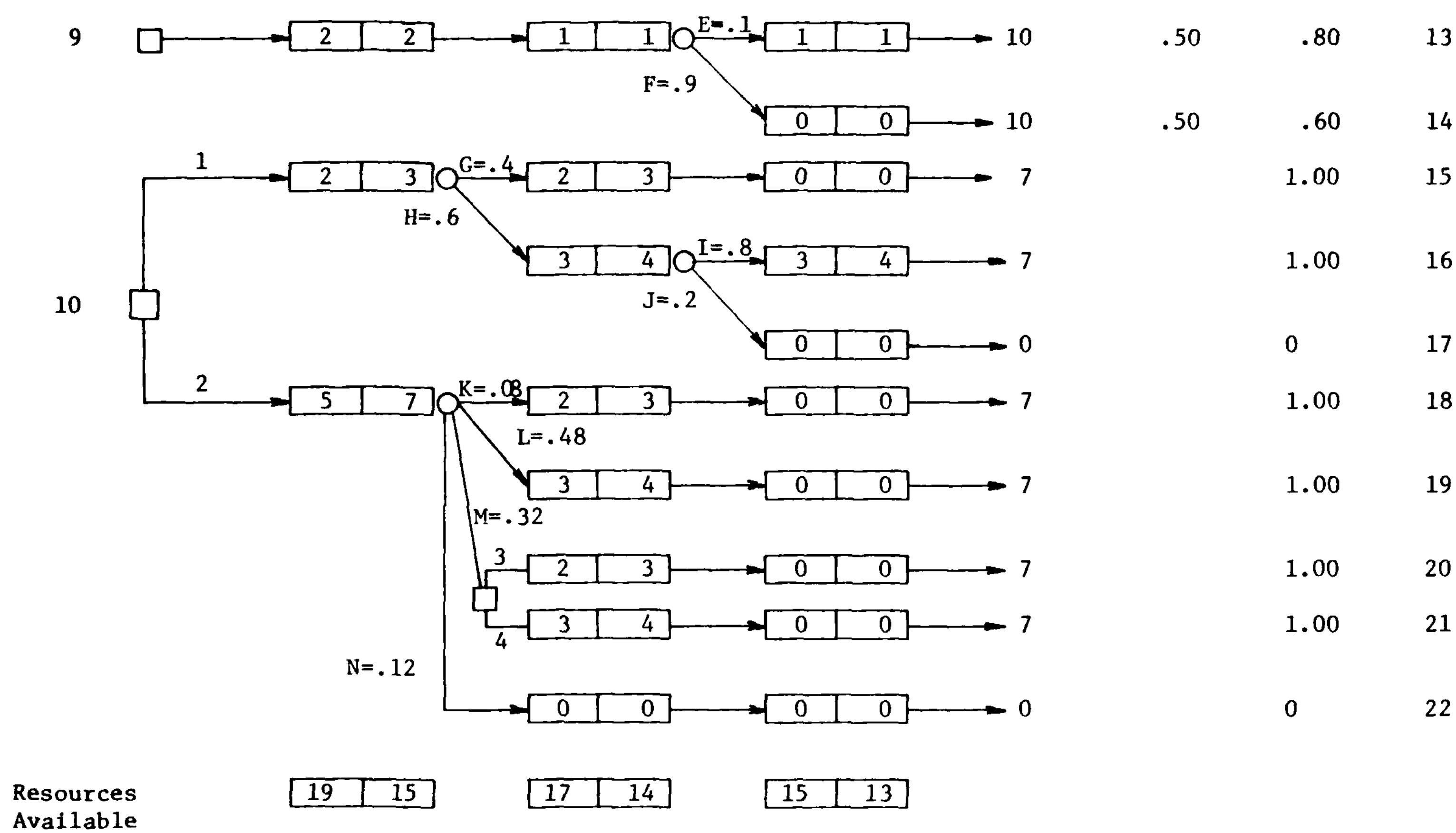
Problem Description and Presentation of the Project Trees

An industrial R&D laboratory must select a portfolio from a set of proposals for projects to be performed over a three year planning horizon. There are two resource categories and a total of ten projects, several of which have multiple versions. Each of these projects, along with their yearly budget and scientific staff resource requirements, is represented in the project trees diagrammed in Figure 4-1. The path variable notation in the righthand column is included for project identification purposes. There are nine decision nodes and six chance nodes, the latter involving 14 technological outcome events identified by the branches and probabilities labelled A through N. The probability of occurrence of any future event in combination with other future events will be referred to as a future technological outcome state, or simply, the future state. When discussed, a future state will be identified by the labels of its component event branches; thus, BCFHIL represents one of the 96 future states that could occur over the three year planning horizon. It can be observed that some of the future states are more dominant than others. For example, future state BCFHIL has a probability of occurrence of .09 which is over 500 times more likely than the future state ACEHJK which has a probability of occurrence of less than .0002.

Projects 1 through 5 and 7 through 9 are representative of modeling techniques already described in Chapter III and only a brief description is necessary here. Projects 1 through 4 have deterministic resource requirements and technological outcomes. Project 5 consists of two mutually exclusive project versions with version 1 having a one year start delay. Project 7 has an initial year of research after which uncertainty exists as to the level of resource usage in the second year required to achieve the expected benefits. Project 8 also has an initial year of research after which the uncertain technological outcome, represented by the chance node, reflects project continuation or termination. Project 9 has two periods of development work followed

Figure 4-1
Project Trees for Case Study

Projects	Branch	First Year Budget (10^5 \$)	First Year Staff	Second Year Budget (10^5 \$)	Second Year Staff	Third Year Budget (10^5 \$)	Third Year Staff	Benefit (10^6 \$)	Increase in Mkt Share (%)	Prob. of Success	Path Var.
1		2	2	3	2	3	2	5	.25	1.00	1
2		1	1	1	1	1	1	4	1.50	.50	2
3		2	1	2	1	0	0	7	1.00	.40	3
4		0	0	2	1	2	1	4	1.00	.80	4
5	1[a]	0	0	3	3	3	3	8	.50	.75	5
	2	3	3	3	3	0	0	10	.50	.40	6
6	1	4	3	1	2	1	2	9	.50	.50	7
	2	7	5	2	4	1	2	24	1.00	.40	8
7	A=.3	1	1	3	1	0	0	9	1.50	.60	9
	B=.7			2	3	0	0	10	1.50	.50	10
8	C=.6	2	2	2	2	2	2	15	1.50	.60	11
	D=.4			0	0	0	0	0	0	0	12



[a]Indicates a mutually exclusive project version.

by the uncertain outcome of either additional work required or early completion. Projects 6 and 10 represent modeling extensions discussed in the next subsections.

Project Tree Modeling of Mutually Dependent Projects

Project 6 is used to illustrate the method suggested for modeling dependent project interrelationships. This project actually represents two distinct projects, one of which is shown as path variable 7 in Figure 4-1, and hereafter referred to as project 6-1. The other project is not included directly in the figure and will be referred to as project Z. Project Z requires spending levels of \$ 300,000 in year 1 and \$ 100,000 in year 2, and 2 scientists in years 1 and 2. The anticipated benefit of project Z is \$ 15,000,000 and it is expected to increase the firm's market share by .5 percent. Commercially, the projects are mutually dependent and, technically, if Z is selected, project 6-1 must also be included in the portfolio although project 6-1 may be selected by itself. The probability of commercial success of project Z is .40; and this probability, given that project 6-1 is successful, increases to .80. The probability of project 6-1 being successful given that Z succeeds, is 1.00. With this information, a new project version, noted as path variable 8 is generated and shown in Figure 4-1. This version represents the resource requirements for both projects Z and 6-1 and the combined benefits of each. The probability of commercial success is the probability of both projects Z and 6-1 being successful:

$$p(Z \cap 6\text{-}1) = p(Z)p(6\text{-}1|Z) = p(6\text{-}1)p(Z|6\text{-}1) = .40 \qquad (4.1)$$

Following this method, the final decision tree for project 6 now represents two mutually exclusive project versions. If the version represented by path variable 7 is selected, only project 6-1 will be funded. If path variable 8 is selected, then both projects Z and 6-1 will be funded. Of course, neither version may be selected in the final portfolio.

Project Tree Modeling of Parallel Versus Series Strategies

When there exists more than one approach for conducting a research project, Abernathy and Rosenbloom[1] suggest that decision makers should examine the relative merits of a parallel strategy before adopting the normally used series strategy. The strategy of employing, in parallel, several research or development approaches to the same objective has also been suggested elsewhere, especially in military development policy. For instance, Mansfield's research[2] found that in weapons systems development programs, Burton Klein[3] of the Rand Corporation suggested parallel development efforts be used to overcome difficult technological problems; and Peck and Scherer argued for parallel approaches when the weapons development program represents a major state-of-the-art advance and minimizing development time is critical.[4]

The series strategy involves selecting one of the multiple approaches for research. In the case of technical outcome failure, another approach is then initiated and so on, until success occurs or all of the alternative approaches have failed. The other strategy involves funding all approaches in parallel and continuing until a clear choice can be made towards the objectives. Note that parallel approaches are not to be confused as duplicate projects since they involve distinctly different means to the same end objective. Generally, a series strategy results in a longer commitment of resources whereas the parallel strategy requires greater resource commitment in the initial periods. Project 10 is included to illustrate the modeling techniques suggested to incorporate these strategies into the project tree format.

Project 10 represents a fixed fee contract for a process modification that, if technically successful, would result in an estimated \$ 7,000,000 reward in follow-on contracts for the firm.[5] Two alternative approaches, which do not appear directly in Figure 4-1, exist for conducting the development work. The first approach, hereafter referred to as approach 10A, requires funds of \$ 200,000 and 3 scientists in the first two years of development work, and the second, hereafter referred to as approach 10B, requires \$ 300,000 and 4 scientists in the first two years. It is assumed that after the first year of development, the progress made on either approach will be sufficient to indicate project success or failure. After the initial year of work is conducted, 10A has a probability of technical success of .40 and 10B has a probability of technical success of .80. The decision to be made is, if project 10 is selected, should a parallel or series strategy be adopted for the two available approaches to the project.

The series strategy is represented by path variables 15 through 17 in Figure 4-1. For the series strategy, one of the two approaches is selected for research funding (Abernathy and Rosenbloom suggest the preferred approach, which is defined as the "apriori best evident" approach, be initiated first[6]). In this case, let the preferred approach be 10A, represented by path variable 15 in the figure, as, even though the probability of success is lower than 10B, a substanially smaller budget commitment is required in the first period. If this approach is successful, it is carried on to completion. If not, research work is initiated on approach 10B, indicated as path variable 16 in Figure 4-1. Thus, the series strategy could result in a three year time commitment if the first approach fails. Note that path variable 17 is included to represent the case where both approaches have failed and the research work is unsuccessfully terminated.

The alternative strategy is to initiate research work on both approaches simultaneously and continue funding that version which indicates technical success after the first year. Thus, as shown by path variable 18 in Figure 4-1, the first year resource commitment is the sums of the budget and staff required for both approaches. After the first year in development, four outcomes are possible and shown in the project tree:

1) Future event K: Approach 10A is successful, 10B is not. The probability of this outcome is:[7]

$$p_{10A}\ (1-p_{10B}) = .4(.2) = .08 \qquad (4.2)$$

2) Future event L: Approach 10B is successful, 10A is not. The probability of this outcome is:

$$p_{10B}\ (1-p_{10A}) = .8\ (.6) = .48 \qquad (4.3)$$

3) Future event M: Both approaches are successfui. The probability of this outcome is:

$$p_{10A}\ p_{10B} = ,4\ (.8) = .32 \qquad (4.4)$$

4) Future event N: Both versions fail. The probability of this outcome is:

$$(1-p_{10A})\ (1-p_{10B}) = .6\ (.2) = .12 \qquad (4.5)$$

If future event M occurs, a decision node is shown at the beginning of the second year, since both approaches 10A and 10B indicate technical successes after the first year and a choice must be made as to which approach to continue. With the same reward anticipated, it would seem that the correct choice would be approach 10A (path variable 20) since the resource commitment is less than that required for 10B. However, one of the multiple goals (to be described in the following section) is to minimize the underutilization of the 14 scientists in the second year and it may be advantageous to select the approach requiring one more scientist under certain situations, such as the need to pursue some sort of work force smoothing policy.

Zero-One Goal Programming Model Formulation

Two experiments will be presented to illustrate the potential capabilities of the zero-one goal program as a decision aiding mechanism. The first concerns analysis of portfolios and associated goal attainment levels for several of the future outcome states of interest to the model users. The second concerns analysis of results when goal priority levels are changed. In each experiment, the technique of simulating dominant future outcome states is used to select the path variables (associated with the chance nodes) for input into the zero-one goal programming formulation. This method is chosen rather than using a stochastic goal programming formulation, because, with 96 future states possible over two time periods, each having two resources to account for, the number of model constraints and variables becomes unwieldy in a stochastic formulation. In addition, aside from the size problem, simulation, or forced future state, selections enable the decision makers to analyze strategies associated with dominant or otherwise selected future outcomes as has been previously discussed. Both experiments will also involve simulation studies to determine how sensitive the various portfolio strategies selected by the zero-one goal programming algorithm are to a range of values for selected system parameters.

A complete goal programming model, as outlined in other applications,[8] is developed in the following steps:

1) Identify decision and deviational variables.

2) Establish model objectives and their priorities.

3) Formulate goal and system constraints.

4) Analyze model output.

Since the R&D selection problem is to determine which projects to include in the research portfolio, the decision variables are:

$$x_j = \begin{cases} 1 \text{ if path variable } j \text{ is selected} \\ 0 \text{ otherwise.} \end{cases} \tag{4.6}$$

The path variable notation has been adopted for ease of representation. Reference is made to Figure 4-1 for interpretation of the x_j's. For example, x_{17} represents version 3 of project 10, given that future event M is under consideration or has occurred (from the original description of project 10, this also represents approach 10A). The deviational variables are n_i, representing negative deviation from goal i, and p_i, representing positive deviation.

For the second and third steps, the following goals and related constraint equations, shown in Table 4-1, are developed. In this illustration, the constraint equations are for future outcome state BCFHIM and are typical of the constraint equations for other future states used in Experiments 1 and 2.

Priority 1: Ensure that only one of the mutually exclusive versions of a project is selected if the project is included in the final portfolio. This goal, although considered a system constraint to ensure solution feasibility, represents the most important objective since unplanned duplication of effort should be avoided in any final portfolio. The goal is achieved by minimizing the negative deviational variables in rows 1 - 3 of Table 4-1.

Priority 2: Limit the research portfolio to no more than four projects expected to take more than two years in the research and development phase. This goal reflects the decision maker's interest in achieving a balance between long and short run projects. It is achieved by minimizing p_4 in the row 4 equation.

Priority 3: Limit the portfolio to no more than two projects with an expected probability of success less than .50. This goal quantifies the desire to limit the number of risky, high return projects in the portfolio. It is satisfied by minimizing p_5 in the row 5 constraint equation.

Priority 4: Maximize the expected benefit of the portfolio. The related constraint equation for this goal is shown in row 6 and the goal

Table 4-1
Model Constraints for Case Study Example

Variables

Row No.	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_{10}	X_{11}	X_{14}	X_{16}	X_{20}	X_{21}	n_i	p_i	Sign	RHS
1					1	1									n_1	$-p_1$	=	1
2							1	1							n_2	$-p_2$	=	1
3												1	1	1	n_3	$-p_3$	=	1
4	1	1		1	1		1	1		1		1			n_4	$-p_4$	=	4
5			1			1		1							n_5	$-p_5$	=	2
6[a]	5	2	2.4	3.2	6	4	4.5	9.6	5	9	6	7	7	7	n_6	$-p_6$	=	100
7[b]	2	1	2			3	4	7	1	2	2	2	5	5	n_7	$-p_7$	=	19
8[b]	3	1	2	2	3	3	1	2	2	2	1	3	2	3	n_8	$-p_8$	=	17
9[b]	3	1		2	3		1	1		2		3			n_9	$-p_9$	=	15
10	2	1	1			3	3	5	1	2	2	3	7	7	n_{10}	$-p_{10}$	=	15
11	2	1	1	1	3	3	2	4	3	2	1	4	3	4	n_{11}	$-p_{11}$	=	14
12	2	1		1	3		2	2		2		4			n_{12}	$-p_{12}$	=	13
13[c]	.25	.75	.40	.80	.375	.20	.25	.40	.75	.90	.30							

[a](10^6 \$); [b](10^5 \$); [c]%

is achieved by minimizing n_6 from a large, unattainable RHS value of \$ 100,000,000. Note that the technological coefficients are the respective probabilities of success times the benefit values from Figure 4-1.

Priority 5: Minimize yearly budget overruns. This goal is represented by three constraint equations shown as rows 7 - 9, and is satisfied by minimizing p_7, p_8, and p_9 from the respective RHS total budget levels.

Priority 6: Minimize underutilization of the scientific staff in each time period. This goal is achieved by minimizing the negative deviational variables in rows 10 through 12.

Priority 7: Maximize the total expected percent increase in market share. This goal is achieved by minimizing n_{13} in row 13. Note that the technological coefficients are the probabilities of commercial success times the respective market share increase values for each variable as shown in Figure 4-1.

The objective function for this case study example includes minimizing the deviations from the set goals with established preemptive priority factors P_k such that $(P_1 > P_2 > \ldots > P_k)$:

$$\text{Minimize } a = \Big[P_1(p_1 + p_2 + p_3);\ P_2(p_4);\ P_3(p_5);\ P_4(n_6);\ P_5(3p_7 + 2p_8 + p_9);\ P_6(3n_{10} + 2n_{11} + n_{12});\ P_7(n_{13})\Big] \qquad (4.7)$$

Note that weights have been assigned to the positive and negative deviational variables at priority levels 5 and 6 to ensure that earlier year resource utilization goals are satisfied before later year goals.

The rationale for this within priority weighting is that less flexibility for budget or personnel adjustments exists in the earlier years. In actual practice, R&D decision makers would be responsible for developing relative within priority weighting schemes as appropriate for the situation. The example is used here to illustrate that cardinal rankings are possible for commensurate subgoals in goal programming formulations.[9]

Experiment 1: Dominant Future State Analysis

For this experiment, the decision makers are interested in examining the different goal attainment levels resulting from the portfolios associated with different future event scenarios represented by the future states previously described in the Figure 4-1 project trees. Six of the 96 possible future states have a combined theoretical probability of occurrence of 37 percent and were chosen as the future states most likely to occur, and therefore, are of interest to the decision makers. Six runs of the zero-one goal programming computer program were made, one for each future state parameter inputs. The results of the six runs, identified as benchmark models 1 through 6, are shown in Table 4-2.

The next step involves a simulation study to determine how sensitive the various portfolio strategies are to a range of values for the system parameters. For this experiment, only the benefit values vary although other variables, such as the probabilities of commercial success and resource availabilities can be included as non-deterministic parameters. The hypothesis to be tested involves determining whether or not the different portfolios generated for the dominant future states

Table 4-2
Experiment 1: Portfolios and Goal Attainment Levels[a]

Model	1	2	3	4	5	6
Future State	BCFHIL	BCFGL	BDFHIL	BCFHIM	BDFGL	BCFGM
Frequency	.087	.073	.058	.058	.048	.048
Path Variables[b]	1-3-5-8 10-11-14-19	1-3-5-8 10-11-14-15	1-3-4-5 8-10-14-19	1-3-5-8 10-11-14-20	1-3-4-5-8 10-12-14-15	1-3-5-8 10-11-14-15
Goal 4: Benefit Attained (10^6 \$):	50.0	50.0	44.2	50.0	44.2	50.0
Goal 5: Budget Overruns (10^5 \$):						
t=1	2	0	0	2	0	0
t=2	1	0	1	0	0	0
t=3	0	0	0	0	0	0
Goal 6: Idle Staff:						
t=1	0	0	0	0	0	0
t=2	0	0	0	0	0	0
t=3	4	4	5	4	5	4
Goal 7: % Increase in Market Share	3.375	3.375	3.275	3.375	3.275	3.375

[a]The first three goals were attained in each model.

[b]Using the path variable notation from Figure 4-1.

of interest result in significantly different goal attainment levels for the fourth priority objective (which represents the maximization of benefit values that are now input as non-deterministic parameters; and which also represents the highest priority goal which might be adequately compared since the first three goals were attained in each model as shown in Table 4-2). For this step, minimum and maximum benefit values are estimated for each project version as shown in Table 4-3. When nothing except the range values are known, Chan[10] suggests the uniform distribution be used to generate parameter values as this maximizes the uncertainty of the simulated environment. Accordingly, a computer code was written in Fortran IV to generate uniformly distributed benefit values and calculate the fourth priority goal attainment for each of the six models and associated portfolios. This process was repeated for 30 observations of each model using six different seeds for the IMSL random number generator used.[11] Table C-1, Appendix C, contains the observations, means and variances of the benefits achieved for each model. The mean benefit values are also provided in Table 4-4 shown on page 81. It is noted that in addition to range distributions, Asher,[12] Elnicki,[13] and Cochran, et. al.,[14] found that R&D decision makers often estimate empirical distributions for the benefit parameters by providing the pessimistic, most likely and optimistic estimates and their associated probabilities. These empirical or any other type of statistical distributions could be represented in the project trees and simulation used to generate benefit values based upon the distributions, as was done in Table 4-4.

A one-way factor analysis of variance test was used to determine if there is a significant difference in the benefits achieved for each

Table 4-3
Experiment 1
Benefit Values

Path Variables	Benefit Range Minimum	(10^6 \$) Maximum
1	3	7
2	3	5
3	4	10
4	2	6
5	5	11
6	5	15
7	6	12
8	16	32
9	7	11
10	8	12
11	12	18
12	0	0
13	8	12
14	7	13
15	7	7
16	7	7
17	0	0
18	7	7
19	7	7
20	7	7
21	7	7
22	0	0

Table 4-4
Mean Benefit Values

(10^6 \$)

Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
49.83	50.43	44.88	49.55	44.50	51.91

model. The ANOVA table appears as Table C-2, Appendix C, and the conclusion is that there exists a significant difference between the mean benefit values of the six models. The next test is to determine which means are different through multiple comparison analysis. The multiple comparison test, reported in Table C-3, Appendix C, resulted in no difference between the means of models 1, 2, 4 and 6 and no difference between the mean benefits of models 3 and 5. However, the mean benefits of the first group are all significantly higher than those of the second. At this point, it is concluded that different portfolio strategies are suggested according to which of the dominant future states occur, but four of the strategies would result in attainment levels which are statistically indistinguishable for the four highest priority goals. Further analysis of these four portfolios and associated models reveals two major decisions occurring at the completion of the first year; namely, the decision to select path variable 15 or 16 (assuming that path variable 17 is the result of unanticipated events occurring during the second year), and the decision to select path variable 19 or 20. Referring to Table 4-2, either of these strategies would result in the same attainment levels for the sixth and seventh priority goals but the portfolio associated with models 2 and 6 outperforms on the budget goal.

These results are then fed back to the decision makers responsible for proposal data generation and to those responsible for final project selection. The benefit of this approach is that decision makers can have the model generate portfolios and goal attainment levels for selected future technological events. Trade-offs can be analyzed and the interactive flow between decision makers and the model continues until consensus is reached with respect to future outcome analysis and portfolio selection. For the problem at hand, the portfolio associated with models 2 and 6 results in the highest goal attainment levels. The other portfolio leads to expected budget overruns and since authoritative sources such as Meadows,[15] Peck and Scherer,[16] and Mansfield, et. al.[17] report cost overruns as common place in the R&D environment, planned overruns are normally avoided.

Experiment 2: Priority Structure Analysis

The dilemma at the completion of Experiment 1 is that the portfolio associated with model 1 (which leads to a planned budget overrun) is the portfolio generated by the goal programming algorithm using as input the future state most likely to occur, namely BCFHIL. It may be of interest, therefore, to determine what portfolio strategy is suggested by the algorithm for this future state if the budget goal is made a higher priority goal.

This type of analysis is also suggested when the decision makers cannot, after several pairwise comparison experiments, achieve a comfortable degree of consensus on the priorities of the six established multiple objectives. Thus, this experiment could also represent the case where, for example, the scientists favored the priority structure used in the conduct of Experiment 1, whereas the laboratory director and division chiefs placed more importance on minimizing budget overruns, a situation which can be expected from the value differences existing between these two groups.[18]

The new priority structure for this experiment therefore places more importance on the budget goal and the complete set of revised "administrators'" priorities is as follows:

Priority 1: Ensure that only one of the mutually exclusive versions of a project is selected if the project is included in the final portfolio.

Priority 2: Limit the research portfolio to no more than four projects expected to take more than two years in the research and development phase.

Priority 3: Limit the portfolio to no more than two projects with an expected probability of success less than .50.

Priority 4: Minimize yearly budget overruns.

Priority 5: Maximize the expected benefit of the portfolio.

Priority 6: Minimize underutilization of the scientific staff.

Priority 7: Maximize the total expected percent increase in market share.

The hypothesis to be tested concerns whether or not different portfolios with different goal attainment levels are suggested by the different priority structures. For this experiment, another run of the goal programming algorithm was made using the same future state and other input data as was used for model 1 in Experiment 1, except for changing the priority structure to the one favored by the laboratory management group. The results of this new run are shown under Model 1A of Table 4-5 along with the original model 1 results from Experiment 1 (Table 4-2). As can be seen here, the revised priority structure results in a different portfolio and, consequently, different goal attainment levels.

The next step in this experiment is a simulation study used to determine how sensitive the portfolio strategies are to a range of values for the system parameters. The benefit values are allowed to vary over the ranges previously shown in Table 4-3. The same computer code used in Experiment 1 was used to generate uniformly distributed benefit values and calculate the fourth priority goal attainment level for model 1 and the fifth priority goal attainment level for model 1A. This process was repeated for 30 observations of each model using the same random number generator seed for the generator used. In this manner, observations were matched in the sense that internally generated random numbers and seeds were the same, the only difference being the different portfolios for the two priority structures. The observations on the benefit functions and statistical analysis are reported in Appendix D. The mean expected benefit of model 1 is $ 50,716,000, which is significantly greater than that of model 1A which is $ 48,895, 000. This information, together with a comparison of the other goal attainment levels shown in Table 4-5, would now be used by the decision makers for further analysis.

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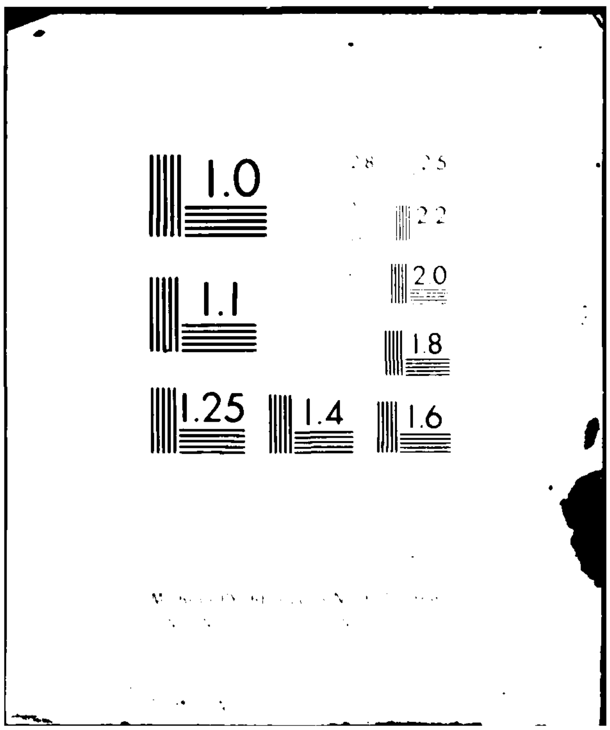
1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8

Table 4-5
Experiment 2
Portfolios and Goal Attainment Levels[a]

Model	1	1A
Future State	BCFHIL	BCFHIL
Path Variables[b]	1-3-5-8 10-11-14-19	3-4-5-8 10-11-14-19
Benefit Attained (10^6 \$):	50.0	48.2
Budget Overruns (10^5 \$):		
t=1	2	0
t=2	1	0
t=3	0	0
Idle Staff:		
t=1	0	0
t=2	0	0
t=3	4	5
% Increase in Market Shr:	3.375	3.925

[a]The first three goals were reached in each model.

[b]Using the path variable notation from Figure 3-4.

In actual applications where consensus concerning the goal priority levels could be blocked, and the integer goal program is used to generate alternate portfolios, several outcomes are possible. First, a common portfolio could emerge for the different priority sets in which case the problem of blocked consensus becomes moot since the same portfolio is suggested no matter which priority structure is used. The second outcome could be that dominant portfolios emerge for each priority set but the goal attainment levels are not significantly different. Again, the problem of blocked consensus is overcome by model results. The third outcome could be the case where dominant portfolios emerge for each priority structure and the respective goal attainment levels are significantly different. This outcome occurred in this experiment. The significantly higher benefit of model 1 requires, as expected, an increase in the funding level of \$ 300,000 in the first two years. Model 1A reflects one more scientist idle in year 3 but, according to the weights, this is not a critical time period. Finally, the portfolio associated with model 1A reflects a higher expected increase in the expected market share. The quantitative analysis suggests the model 1A portfolio as the favored strategy since the incremental expected return of model 1 is substantially less than the return of model 1A. The final decision, however, rests with the decision makers and all results are provided to them for further analysis. The benefit of using the model results in interaction with the decision makers is to afford them suggested strategies and goal attainment levels for the alternatives presented. In the case study, if the management and staff groups do not achieve consensus in selecting one of the two portfolios, the last resort is to examine the dominant projects that appear in the two portfolios of Table 4-5. Projects 3, 5 (version 1), 6 (version 2), 7, 8, 9 and 10 (version 2) should be selected no matter which priority structure is agreed upon. The second priority structure suggests project 4 should be included whereas project 1 is suggested by the other structure. To assist in the final selection, qualitative techniques such as paired comparison experiments,[19] may be utilized.

Dominant Project Analysis

In concluding this chapter, it is of interest to discuss the alternative simulation approach suggested by Lockett and Gear[20] and Lockett and Freeman[21] for those applications where problem size prohibits stochastic program formulations. Their technique uses a simulation model to sample the chance nodes of the project tree in order to determine the future event branches and associated path variables to be input into a linear or integer mathematical program. The portfolio suggested by solving the program is recorded and the entire process repeated for the number of observations desired. A final portfolio "is built up" by selecting those projects which appeared most often in the portfolios generated, or by some other qualitative analysis, until the resources are fully utilized.[22]

This approach was extended to the multiple objective R&D project selection problem presented in Figure 4-1, using the multiple goals and priority structure of Experiment 1. A simulation model was written in Fortran IV to sample the chance nodes of the decision trees and the range distributions of the benefit values (Table 4-3). The generated path variables associated with chance outcome future events, benefit values and other pertinent project tree data were used as input to the zero-one goal programming algorithm and the portfolio suggested by running the program was recorded. This procedure was repeated for 30 observations and the project frequencies in the output results are shown in Table 4-6. Project 1, 5 (version 1), 6 (version 2), 7, 8 and 9 are dominant and should be included in the final portfolio. The remaining problem is: which of the projects not yet selected should be included in the final portfolio?

A disadvantage of this approach is that the project selection problem may not be solved at the completion of the programming model runs and an alternative approach is required to complete the portfolio. This was the case in the above illustration.

Table 4-6
Dominant Project Frequencies

Projects	Versions	Path Variables	Number of Times Path Variable Appeared in Selected Portfolio
1		1	28
2		2	3
3		3	22
4		4	17
5	1	5	21
	2	6	9
6	1	7	1
	2	8	29
7		9	10
		10	20
8		11	16
		12	4
9		13	4
		14	26
10	1	15	14
	1	16	1
	1	17	0
	2	18	1
	2	19	9
	3	20	5
	4	21	0
	2	22	0

Footnotes

[1]W. J. Abernathy, and R. S. Rosenbloom, "Parallel Strategies in Development Projects," Management Science, Vol. 15 (June, 1969), pp. B486-B505.

[2]E. Mansfield, Technological Change (New York: W. W. Norton & Company, Inc., 1971), p. 144.

[3]B. H. Klein, "Policy Issues Involved in the Conduct of Military Development Programs," Economics of Research and Development, ed. R. A. Tybout (Columbus, Oh.: Ohio State University Press, 1965), p. 322.

[4]M. J. Peck, and F. M. Scherer, The Weapons Acquisition Process: An Economic Analysis (Boston, Mass.: Div. of Research, Graduate School of Business Admin., Harvard University, 1962), pp. 306-307. It is noted that Peck and Scherer also argued that the parallel strategy is not always optimal, especially when weapons systems quality is important but minimizing development time is not.

[5]E. B. Roberts, and W. H. Dyer III, "Follow-On Contracts in Government-Sponsored Research and Development: Their Predictability and Impact," Industrial Management Review, Vol. 9 (Winter, 1968), pp. 41-55.

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[7]Ibid.

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[9]S. M. Lee, Goal Programming for Decision Analysis (Philadelphia, Pa.: Auerback Publishers, Inc., 1972), p. 43.

[10]M. M. W. Chan, "System Simulation and Maximum Entropy," Operations Research, Vol. 19 (1971), pp. 1751-1753.

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[15]D. L. Meadows, "Estimate Accuracy and Project Selection Models in Industrial Research," Industrial Management Review, Vol. 9 (Spring, 1968), pp. 105-119.

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[17]E. Mansfield, J. Rapoport, J. Schnee, S. Wagner, and M. Hamburger, Research and Innovation in the Modern Corporation (New York: W. W. Norton & Company, Inc., 1971), Chap. 5.

[18]A. Zaleznik, G. Dalton, L. Barnes and P. Laurin, Orientation and Conflict in Career (Boston, Mass.: Div. of Research, Graduate School of Business Administration, Harvard University, 1970).

[19]W. E. Souder, "Achieving Organizational Consensus with Respect to R&D Project Selection Criteria," Management Science, Vol. 21 (February, 1975), pp. 669-681.

[20]A. G. Lockett, and A. E. Gear, "Representation and Analysis of Multistage Problems in R&D," Management Science, Vol. 19 (April, 1973), pp. 947-960.

[21]____________, and P. Freeman, "Probabilistic Networks and R&D Portfolio Selection," Operational Research Quarterly, Vol. 21 (September, 1970), pp. 353-359.

[22]Lockett and Gear.

CHAPTER V

MODEL APPLICATIONS

While the purpose of the previous chapter was to examine the conceptual utility of the proposed model, the emphasis in this chapter is on the practical utility of the model. This will be performed by examining the efficiency and validity of the proposed model through comparison of its results with those of other state-of-the-art mathematical programming models. Three previously published R&D project selection problems, two of which represent actual studies, are used for the data input. In addition, to further assess the feasibility of the model and gain a broader insight into actual decision making processes, interview sessions were conducted with R&D administrators of five diverse enterprises, in order to discuss the proposed multiple objective project selection and resource allocation model in the context of the R&D decision making process unique to each of the five organizations. Specifically, the nature of the project selection decision was examined with regards to the realism, applicability, feasibility and limitations of the proposed formal decision aiding tool. Finally, as an outcome of the interview with the director of the research laboratory of a large textile firm, an actual application of the model was developed and is presented.

Efficiency and Validity Comparisons

Application 1: A Static Single Objective Case

Most of the quantitative models proposed for the R&D project selection problem involve linear or zero-one programming formulations for the single objective, single period, case. Although the proposed model, hereafter referred to as the thesis model, was designed to incorporate multiple objectives and multiple periods with uncertainty, it must be capable of providing good solutions to the specific class of single objective problems in order to enhance its general applicability.

To test the validity[1] and efficiency of the thesis model, a "real world" problem presented by Souder[2] was selected and solved using both the thesis model and the efficient zero-one algorithm developed by Mandakovic.[3] The model proposed by Mandakovic was chosen as representative of the state-of-the-art algorithms for single objective, integer programming formulations with zero-one variables.[4] Mandakovic developed two algorithms in his research, both of which employ the Senju-Toyoda[5] and Toyoda[6] primal effective gradient method for solving formulations of the type shown by equations (2.1) - (2.6) in Chapter II. Mandakovic's initial algorithm involves selection of that project or project version having the maximum index of profitability for a given level of resource(s), deducting the resources consumed by the selected project from the total available, and repeating the selection procedure until the critical resource is exhausted. The index of profitability is defined as the rate of return per unit of resource used. The second algorithm developed by Mandakovic was specifically designed for hierarchical R&D organizations and decomposes the selection problem into two parts; one for the superordinate level and the other for the subordinate level. An interactive mode is used for communication of budget levels (from superordinate to subordinate) and selected project versions (from the subordinate to superordinate). Both algorithms, being based on heuristic techniques, were designed to rapidly produce good results for medium to very large scale problems.[7]

The input data from Souder[8] involves a 30 project problem solved in this case for the start of the budget period. The maximum funding levels for each project and the maximum expected project values are shown in Table 5-1. Each project can be selected in one of three versions; where the first version represents a project consuming 25% of the maximum funding level; the second, a 50% funding level; and the third, the maximum funding level. Associated with each of the 90 resulting project versions is a probability of success shown in Table 5-2 which, when multiplied by the project value, gives the expected gross return for the particular version. The objective is to maximize the total expected return of the portfolio chosen subject to the budget constraint, mutually exclusive project version constraints, and the zero-one variable restrictions.

Souder's problem was decomposed into nine subproblems by varying the number of variables and the total budget available as shown in Part 1 of Table 5-3. Subproblem 1 includes the first 10 projects and their respective versions, funding levels and expected returns, subproblem 2 includes the first 15 projects and associated parameters, and so on until all 30 projects are included in subproblems 7, 8 and 9. The budget level was set at approximately 45% of the sum of the project maximum funding levels for each subproblem except 3, 5, 8 and 9 which

Table 5-1
Data for Application 1

Project Number	Maximum Funding Level ($ 000)	Project Value ($ 000)
1	300	11,600
2	600	16,200
3	700	12,000
4	250	10,500
5	200	22,900
6	450	13,100
7	300	15,600
8	500	20,500
9	200	11,500
10	200	13,500
11	300	22,100
12	300	5,500
13	150	15,500
14	500	20,000
15	200	7,500
16	350	12,000
17	150	20,000
18	500	8,500
19	100	12,000
20	300	8,500
21	200	21,500
22	100	11,800
23	400	18,500
24	350	7,000
25	600	14,000
26	600	20,500
27	100	6,000
28	250	12,500
29	600	18,100
30	400	5,500

Table 5-2
Probabilities of Success for
the Various Funding Levels
Application 1

Project Number	Version 1 (p_1)	Version 2 (p_2)	Version 3 (p_3)
1	.20	.30	.50
2	.20	.40	.70
3	.30	.30	.65
4	.10	.25	.80
5	.10	.50	.75
6	.30	.70	.65
7	.30	.50	.90
8	.20	.55	.90
9	.25	.30	.50
10	.05	.35	.80
11	.10	.50	.70
12	.10	.20	.60
13	.10	.20	.60
14	.00	.10	.50
15	.10	.20	.70
16	.10	.30	.70
17	.10	.30	.70
18	.10	.20	.60
19	.05	.10	.50
20	.10	.30	.70
21	.10	.70	.80
22	.30	.80	.90
23	.10	.70	.80
24	.30	.80	.90
25	.30	.90	1.00
26	.40	.30	.90
27	.40	.70	.80
28	.20	.80	.90
29	.30	.90	.90
30	.30	.80	.90

Table 5-3
Model Comparisons: Application 1
(All $ Figures in 000's; CPU Time in Seconds)

	Subproblems								
	1	2	3	4	5	6	7	8	9
1. Description									
a. Variables	30	45	60	60	60	75	90	90	90
b. Budget ($)	1,640	2,285	1,650	2,905	4,950	3,635	4,500	5,050	5,300
2. Mandakovic's Model									
a. Return ($)	67,880	93,455	94,560	123,655	143,530	177,995	224,910	234,410	239,760
b. CPU Time	.2	.2	.5	.3	.3	.4	.4	.5	.4
3. Thesis Model									
a. Return ($)	76,970	104,790	96,850	134,060	171,695	178,580	232,360	247,020	253,620
b. CPU Time	2.8	13.6	17.8	31.0	20.8	133.5	281.5	313.6	265.7
4. Models Used by Souder*									
a. Return: Zero-One Model ($)							207,000	212,000	216,000
b. Return: Linear Model ($)							207,000	228,000	239,000
c. Return: Nonlinear Model ($)							232,000	249,000	257,000

*Results Reported to Nearest $ Million

examine tighter (subproblem 3) or relaxed (subproblems 5, 8 and 9) levels. Although Mandakovic solved subproblems 7, 8 and 9 and reported the results in his dissertation,[9] a computer code for his initial algorithm was written for these single resource constrained, single time period problems in order to obtain results for subproblems 1 through 6 and CPU times for all of the problems solved.[10] For the thesis model, the single objective subproblems were converted into multiple objective formulations having three goals. The first goal was to ensure that either one or none of the three versions of each project is selected. The second goal was to stay within the budget constraint and the third goal was to maximize the return of the portfolio selected. The variable selection and exchange heuristics (option number 2, as described in Chapter III and in Appendix A) was used to solve all nine subproblem formulations.

Parts 2 and 3 of Table 5-3 provide the comparisons between the two models. In every case, the thesis model outperformed the Mandakovic algorithm with respect to expected net return (sum of the expected values less funds expended). The average improvement in net returns was 8% with a range between .3% and 20%. The validity of the thesis model with respect to this test appears to be established. As expected, the Mandakovic algorithm was very efficient, solving the various subproblems in .2 to .5 seconds. In contrast, the thesis model required from 2.8 to 313.6 seconds. The tradeoff between the heuristic models is thus one of solution performance versus computer time and cost for medium size problem applications. As an extreme example, subproblem 6 illustrates a strategy with an expected return of $ 28,165,000 more for the thesis model at a cost increase of 20.5 seconds.

While there is no theoretical limit to the size problem which the thesis model can address, some practical constraints are imposed by operating time requirements and serve to limit the size problem which the model can realistically consider. However, the range of capability of the thesis model does include most of the realistic size problems encountered in the R&D environment. For multiple objective problems with more than 100 variables, it was suggested in Chapter III that the variable selection heuristic can be used without the exchange routine when CPU time is an important consideration. A 180 variable problem similar in structure to the 90 variable problems reported in this application was created to test the efficiency and validity of the thesis model using only the variable selection procedure. The problem was also solved by the Mandakovic algorithm for comparison purposes. The thesis model required 21 seconds of CPU time compared to .9 seconds for the Mandakovic algorithm; and the solution obtained by the thesis model was 7.7% less than the solution obtained by the Mandakovic algorithm. The variable selection procedure does provide an alternative for larger size problems and, in addition, represents a more direct and realistic approach to addressing multiple objectives than do the single objective models.

To complete the validity evaluation, Part 4 of Table 5-3 provides Souder's original results for subproblems 7, 8 and 9 using zero-one, linear and nonlinear programming algorithms.[11] These results are reported here as they were used by Mandakovic to test the validity of his zero-one algorithm.[12] The thesis model outperformed the zero-one and linear models in every case and equalled the nonlinear solution for subproblem 7. This comparison must be cautiously considered, however, since Souder's zero-one model only included version 3 of each project and the linear and nonlinear optimization was made on continuous variables with the versions being approximated. Thus, according to Mandakovic, the linear and nonlinear solutions are in the superoptimal infeasible area when considering that the zero-one restrictions represent the realistic case.[13]

Application 2: A Multiperiod, Multiple Objective (Dynamic Programming) Case

The second application involved a validity test of the thesis model using a dynamic, noncommensurate multiple objective R&D project selection problem. The state-of-the-art model chosen for comparison purposes is the dynamic programming technique of Rosen and Souder.[14] Up until the introduction of decision tree modeling, the dynamic programming approach was the only method capable of addressing the multistage nature of project evolution along with the consideration of uncertainty. Rosen and Souder further attempted to enhance the realism of their formulation by recognizing the existence of multiple objectives, albeit in an indirect manner. Their method includes the recognition of a set of multiple criteria for a particular case study, one of which is chosen for optimization in their single objective dynamic programming model. Then, using the selected portfolio suggested by the model, the goal attainment levels for the other objectives are calculated. If any of the goals are not attained, the model is rerun with one or more relaxed objectives; with a reduced set of project versions; or with a modification of the constraints.

The problem used to test the validity of the thesis model with respect to the dynamic programming technique is a smaller version of the problem reported by Rosen and Souder in the publication noted above.[15] This problem is an illustration of the type of project selection problems encountered at the Monsanto Chemical Company at the time of publication. Table 5-4 shows the input data for six projects being considered for funding in this case study. Note that only the first year budget constraint is specified for the three period planning horizon. This is necessary due to the dimensionality restrictions of dynamic programming. However, some control over future period spending is possible through manipulation of s^j_{max}, s^j_{min}, and x_{max} which is why these parameters are included. Table 5-5 provides the project success probabilities for the various expenditure levels.[16] The objectives are:

1) Maximize the total anticipated net profit.
2) Achieve a total expected output of at least 6.60.[17] Total expected output is defined as the sum of the probabilities of success for each project version selected over all time periods.
3) Achieve a return on expenditure (ratio of net profit to total funds expended) of at least 45.[18]
4) Obtain a life expected output, defined as the sum of the probabilities of success over all years, of approximately 1.00 for project 12, the selection of which has been predetermined by top management.

To formulate this problem for an application of the thesis model, project trees were developed as shown in Figure 5-1. All of the input

Table 5-4
Input Data: Application 2

Project Name	Project Life (Years)	Total Anticipated Discounted Gross Profit (G^j)	Maximum Spending Level per Year (x^j_{max})	Maximum Spending Level over Project's Life (s^j_{max})	Minimum Spending Level over Project's Life (s^j_{min})
1	1	$ 14,900	$ 60	$ 60	$ 0
6	3	21,000	180	330	0
9	2	11,100	220	400	0
12	2	2,700	180	400	0
16A	2	24,000	270	710	0
16B	1	10,800	70	70	0

All $ figures in 000's.

Discount Rate = r = .1; Discount Factor = p = .909

Superscript j indicates Project Version.

The total first year budget is $ 750.

Table 5-5
Project Success Probabilities
for Various Expenditure Levels
Application 2

$\left[p^{j}(x)\right]$

Expenditure Levels in \$ 000 (x)	Project Name					
	1	6	9	12	16A	16B
0						
20						.65
30	.42					
60	.50			.38		
70						.80
150		.63				
160				.60		
180		.72	.60			
220			.68			
230					.88	
270					.912	

Figure 5-1
Project Trees for Thesis Model
Application 2

Project Name	Funds Yr. 1 ($000)	Funds Yr. 2 ($000)	Funds Yr. 3 ($000)	Expected Profit ($000)	Expected Output	Project Version
1	60	0	0	7,390	.50	1
	30	0	0	6,228	.42	2
6	180	150	0	18,269	1.35	3
	180	0	150	17,966	1.35	4
	180	0	0	14,940	.72	5
	150	180	0	18,105	1.35	6
	150	150	0	17,479	1.26	7
	150	0	180	17,648	1.35	8
	150	0	150	17,079	1.26	9
	150	0	0	13,080	.63	10
	0	180	150	16,607	1.35	11
	0	180	0	13,580	.72	12
	0	150	180	16,457	1.35	13
	0	150	150	15,889	1.26	14
	0	150	0	11,890	.63	15
	0	0	180	12,345	.72	16
	0	0	150	10,808	.63	17
9	180	220	0	9,144	1.28	18
	0	220	0	6,661	.68	19
	220	180	0	9,213	1.28	20
	180	180	0	8,836	1.20	21
	0	180	0	5,890	.60	22
	220	0	0	7,328	.68	23
	180	0	0	6,480	.60	24
12	160	160	0	1,991	1.20	25
	60	160	0	1,789	.98	26
	0	160	0	1,327	.60	27
	160	60	0	1,811	.98	28
	60	60	0	1,510	.76	29
	0	60	0	878	.38	30
	160	0	0	1,460	.60	31
	60	0	0	966	.38	32
16A	270	270	0	23,347	1.824	33
	230	270	0	23,248	1.792	34
	0	270	0	19,651	.912	35
	270	230	0	23,289	1.792	36
	230	230	0	23,169	1.76	37
	0	230	0	18,989	.88	38
	270	0	0	21,618	.912	39
	230	0	0	20,890	.88	40
16B	70	0	0	8,570	.80	41
	20	0	0	7,000	.65	42

data, with the exception of net discounted expected profits, are obtained directly from Tables 5-4 and 5-5. The expected profit functions used in Rosen and Souder's dynamic programming model were also used to compute the expected profit column entries for the decision tree. For example, the expected profit for version 8, project 6, is determined as follows. First, compute the net expected profit with one time period remaining:

$$f_1^8 = G^8 \; p^8(x) - x = 21,000\ (.72) - 180 = 14,940 \tag{5.1}$$

Here, the superscript refers to the proje version and the subscript refers to the number of time peric remaining. Next, compute the net expected profit with two time periods remaining:

$$\begin{aligned} f_2^8 &= \left[G^8 \; p^8(x) - x + p[1 - p^8(x)]\; f_1^8 \right] \\ &= 21,000\ (0) - x + .909[1 - 0]\ (14,940) \\ &= 13,580.46 \end{aligned} \tag{5.2}$$

Finally, compute the expected profit with three time periods remaining:

$$\begin{aligned} f_3^8 &= \left[G^8 \; p^8(x) - x + p\,[1 - p^8(x)]\; f_2^8 \right] \\ &= 21,000\ (.63) - 150 + .909\ [1 - .63]\ (13,580.46) \\ &= 17,648 \end{aligned} \tag{5.3}$$

Note that only feasible project versions are included in the decision trees. For example, project 6 has a three year planning horizon with two versions possible in each time period giving a total of 27 versions. However, some of these versions are infeasible, such as the version having funding levels of \$ 180,000 in each year, since s_{max} of \$ 330,000 is exceeded. The project version labels in Figure 5-1 have been added for identification purposes.

The problem was solved using the dynamic programming recursive equations developed by Rosen and Souder with the objective of maximizing net expected profit for the given budget level and other funding restrictions for each project version. Then, using the project versions selected by the model, the goal attainment levels of the other three objectives were computed. Results are shown in Table 5-6, column (1). Since the return on expenditure objective was not met, Rosen and Souder suggest dropping out low profit projects, relaxing the funding level constraints or relaxing the first or third objective and rerunning the model. Here, the strategy they selected was to relax the return on expenditure goal and accept the solution presented (in the original problem, the return on expenditure goal was relaxed from 55 to 51; for the smaller problem it is relaxed from 45 to 43).

The thesis model was also applied to this problem by incorporating the multiple goals and decision tree data into an integer goal programming formulation. The first goal was to ensure that only one or none of the versions of each project is selected. The second goal is to stay within the \$ 750,000 budget constraint. The fourth goal was to achieve the total expected output of 6.60. The fifth goal was to achieve the life expected output of approximately 1.00 for project 12, and the sixth goal was to maximize the expected net profit. The only objective that could not be directly operationalized in the goal programming model was the return on expenditure goal of 45 since the

Table 5-6
Model Results
Application 2

	(1) Dynamic Programming Model	(2) Thesis Model Solution 1	(3) Thesis Model Solution 2
Budget Level ($)	750,000	750,000	750,000
Project Versions Selected			
Projects			
1	1	2	2
6	6	3	3
9	18	18	18
12	26	26	29
16A	34	34	34
16B	41	41	41
Total Funds Expended ($)	1,580,000	1,550,000	1,450,000
Expected Net Profit ($)	68,246,000	67,248,000	66,969,000
Return on Expenditure ($)	43.19	43.38	46.20
Total Expected Output	6.702	6.622	6.40
Life Expected Output for Project 12	.98	.98	.76

computation requires a nonlinear equation. However, this goal can be easily incorporated by establishing a goal constraint for total expenditure and using several model runs with incremental tightening of the constraint until the return on expenditure goal is met. This goal was assigned as the third priority objective.

The thesis model was run using the variable selection and exchange heuristics and with partitioning on each project version. The results are shown in colums (2) and (3) of Table 5-6. Solution 1 shown in column (2) involved a very loose constraint on the third priority goal (incremental ranges from \$ 1,580,000 to \$ 1,600,000) and the results reflect slight but interesting differences when compared to the dynamic programming solution. The expected net profit is 1.5% less than the Rosen and Souder solution but there is a slight improvement (.4%) on the return on expenditure goal attainment. Both solutions attain the total expected output goal. Rather than changing the return on expenditure goal to 43 and accepting this solution, the model was rerun at tighter total expenditure levels until the return on expenditure exceeded the goal of 45. This goal was achieved with the projects selected and shown under solution 2, column (3) in Table 5-6. The expected net profit is 1.9% less than Rosen and Souder's solution but the return on expenditure goal is now achieved. Note that the total expected output and the project 12 life expected output goals are underattained in this solution. The two solutions presented (for the thesis model) are an example of the decision aiding capability of the thesis model. Model users can readily determine that the simultaneous attainment of the four goals is not possible and the decision to be made is to accept the strategy providing a higher expected profit with a lower return and higher expected successes or to accept a strategy with the reverse results.

<u>Application 3: A Static Multiple Objective (Zero-One Goal Programming) Case</u>

The final efficiency and validity evaluation of the model was performed for a static multiple objective R&D project selection problem. The model chosen for comparison purposes was the zero-one goal programming model presented recently by Keown, Taylor, and Duncan,[19] hereafter referred to as the KTD model. These researchers used the zero-one implicit enumeration algorithm developed by Morris[20] and previously discussed in Chapter III and, because of the recent vintage which the model represents, for all intents and purposes, the current state-of-the-art in multiple objective R&D project selection models.

The problem used for evaluation of the two models is the 20 project hypothetical case study Keown, Taylor and Duncan used in illustrating their approach. Input data is shown in Table 5-7. The study concerns an electrical equipment manufacturer involved in offensive (new product development) and defensive (modification of existing products) projects, and having two sales divisions, two competitive markets and two research centers. To choose a portfolio strategy for the next planning period, the company has established the following 10 goals:

1) Avoid project duplication by selecting a maximum of one version from each of the following project combinations:

Table 5-7
Input Data for Application 3

Project Description*	Cost ($000)	Percent Facilities Required		Staff Required		Prob. of Success	Sales ($000) Anticipated		% Growth in Mkt Shr Expected		Net Present Value ($000)
		Ctr 1	Ctr 2	Ctr 1	Ctr 2		Div 1	Div 2	Mkt 1	Mkt 2	
1 (D,C)	220	18%		5		30%	420		2.67%		180
2 (D,C)	220		15%		5	30%	420		2.67%		180
3 (O,C)	90	14%		7		18%	250		.50%		40
4 (O,C)	300	24%		9		10%	1,500				70
5 (O,M)	390	28%		9		15%	1,233		.80%		100
6 (O,M)	310	35%		5		23%	674		3.47%		130
7 (D,C)	280	23%		6		35%	428		2.86%		80
8 (D,C)	280		20%		6	35%	428		2.86%		80
9 (D,M)	140	20%		2		30%	223				110
10 (D,M)	340	23%		4		25%	660				130
11 (O,M)	320	21%		5		20%	750				60
12 (D,C)	170		25%		3	30%		300		2.00%	40
13 (D,C)	220		20%		8	33%		303		2.27%	110
14 (D,C)	200		18%		4	30%		333		2.33%	70
15 (D,C)	100		14%		4	33%		136		1.12%	30
16 (O,C)	300		19%		2	18%		833			80
17 (O,C)	330		28%		7	10%		1,550			70
18 (O,C)	250		23%		6	18%		666			110
19 (D,C)	420	31%		8		40%		550		3.50	140
20 (D,C)	420		31%		8	40%		550		3.50	140

*D = Defensive Project
O = Offensive Project
C = Civilian Application
M = Military Application

projects 1 and 2, 7 and 8, 9 and 10, and 19 and 20 (these are commonly referred to as mutually exclusive system constraints).

2) Do not exceed an expenditure ceiling of $ 2,100,000.

3) Do not exceed the capacity of the two research facilities.

4) Do not exceed a staff requirement of more than 22 researchers at Center 1 and 25 researchers at Center 2.

5) Select at least two projects representing military applications.

6) Select at least three offensive and five defensive projects for the final portfolio.

7) Achieve a total expected output of at least 2.00 (sum of the probabilities of success for projects selected).

8) Achieve an expected annual sales increase of $ 750,000 in Division 1 and $ 500,000 in Division 2.

9) Achieve an expected increase in market share of 2.80% in Market 1 and 2.20% in Market 2.

10) Maximize the net present value of the projects selected.

The problem was solved using the KTD model (Morris algorithm) and three versions of the thesis model. The results are reported in Table 5-8. For the thesis model, solution 1 represents the results for the variable selection and exchange heuristic. Solution 2 results were obtained by including the partitioning procedure where each mutually exclusive project version was iteratively forced out of consideration for the solution. Solution 3 results were obtained by creating 20 subproblems for the partitioning routine, where each subproblem represents one project forced out of consideration for the solution. From

Table 5-8
Model Comparisons
Application 3

	KTD Model	Thesis Model Soln 1	Thesis Model Soln 2	Thesis Model Soln 3
CPU Time (Seconds)	1202.0	1.3	5.9	14.0
Iterations	53,472	26	208	499
Projects Selected	1-4-6-8-9 12-18-20	1-5-6-8 13-14-15 16	1-3-6-8 14-15-16 18	1-4-6-8-9 14-15-16 18
Goal Achievements				
1. Meet System Constraints	Attained	Attained	Attained	Attained
2. Budget Limit	"	"	"	"
3. Facilities Capacity	"	"	"	"
4. Staff Limit	"	"	"	"
5. Priority Projects Goal	"	"	"	"
6. Offensive-Defensive Balance	"	"	"	"
7. Risk Spreading Goal	"	"	"	"
8. Sales Expected ($)	1,077,600	1,010,480	1,055,420	1,062,320
9. Market Share Expected	4.599%	4.618%	3.758%	3.668%
10. Net Present Value Expected ($)	860,000	780,000	850,000	860,000

an efficiency standpoint, the thesis model is clearly superior with CPU times ranging from 1.3 to 14 seconds compared to just over 20 minutes for the KTD model. It is noted again that 20 variables is the approximate upper limit of the capability of the Morris algorithm. With respect to solution validity, the thesis model was very close to the optimal solution (KTD model) for all versions used. The first seven goals were completely attained by the thesis models as they were in the optimal solution. For the KTD model, the sales goal attainment level was 86.2% of the stated objective. Solution 1 of the thesis model attained 80.8% of this goal, solution 2 attained 84.4% and solution 3 attained 85% of this goal. The market share growth goal was not attained by any of the models. The percent attainment levels were 92% for the KTD model and 92.4%, 75.7% and 73.4% for the three versions of the thesis model. The net present value goal was simply to maximize the net present value of the portfolio. The three versions of the thesis model attained 90.7%, 98.8% and 100% of the optimum goal attainment level of \$ 860,000.

Summary of the Efficiency and Validity Comparisons

The first application involved comparing the thesis model with the integer (zero-one) programming algorithm of Mandakovic for the static single objective case. The thesis model outperformed Mandakovic's model with respect to solution results whereas the reverse was true with respect to program processing times. For very large problems of this type, that is, 1,000 to 10,000 variables, the Mandakovic model is obviously superior. However, two important points must be made. First, the thesis model was not designed for situations where the R&D manager must gather data for and select projects from a set of 10,000 project variables, or even 1,000 project versions. It was designed for medium scale problems with an upper limit of 90 to 100 variables. While the large scale problems have theoretical interest, the medium scale problems represent the realistic situations found in the literature and during the interview sessions with R&D laboratory directors. Secondly, the richness of the thesis model lies in its capability to address multiple, noncommensurate objectives ranked on an ordinal scale; a capability which cannot be evaluated in this application due to the single criterion restriction of Mandakovic's model.

The second application compared the thesis model to Rosen and Souder's dynamic programming model for the multiperiod, multiple objective case. The solution generated by the thesis model was comparable to the dynamic programming solution. To complete the comparison of the two models, it is helpful to point out the advantages and disadvantages of both approaches. The thesis model can incorporate all objectives into the problem formulation (except the nonlinear return on expenditure function which could be indirectly handled), whereas the dynamic programming approach cannot. The dynamic programming model can handle a large number of project variables, whereas the thesis model was designed for medium size problems. On the other hand, the thesis model can handle multiple resource constraints over multiple periods whereas the dynamic programming model is limited to a single constraint in the first stage. In summary, for medium size problems the thesis model can be used to solve any R&D project selection problem solved by the dynamic programming model.

The converse is not true since the dynamic programming technique is restricted to a single constraint and single criteria.

The third application compared the thesis model with the zero-one goal programming algorithm by Morris as applied by Keown, Taylor and Duncan for a single period, multiple objective problem. With respect to solution validity, the thesis model was very close to the optimal solution and the processing times of 1.3 to 14 seconds represented a substantial reduction from the 20 minutes required by the Morris algorithm. Further, it was pointed out that the problem solved by the Morris algorithm represented its' maximum size capability, whereas the thesis model can solve problems with substantially more decision variables. Advantages, in addition to the speed and problem size aspects, of the thesis model in comparison with the KTD model include the capability to address multiple time periods characterized by uncertainty.

Practical Utility of the Thesis Model As Viewed Through Interviews with R&D Managers

Interviews were conducted with R&D managers in five enterprises having professionally staffed and formally organized research and development activities. The enterprises were chosen to be representative of a diversity of organizational types with supporting R&D laboratories, concentrating on a variety of programs ranging from exploratory research for the advancement of knowledge to development projects for new products or processes. A brief description of the sample laboratories and parent organizations is provided on the following page.

Case 1: A research laboratory of a large textile corporation engaged in applied research on domestic textiles.

Case 2: The research and development laboratories of a major pharmaceutical, biological and chemical producer which concentrates on exploratory research programs.

Case 3: A research laboratory of a government regulatory agency involved in applied research, development of standards and control technology.

Case 4: The chemical research division of a major consumer products company engaged in chemical, physical and analytical studies, and in applied research on new products and manufacturing processes.

Case 5: A center for technology applications of an independent, not-for-profit research institute involved in basic and applied research in medical and related sciences. Research work is conducted on a fee or contract basis with government, industry and foundation organizations.

The interview sessions involved presentation of the multiple objective project selection and resource allocation model followed by discussions of the R&D decision making processes unique to the five organizations. Specifically, the nature of the project selection decision was examined with regards to the realism, applicability, feasibility and limitations of the thesis model. A summary of the findings for each of the five organizations is described next.

Case 1

The director of research for the textile corporation has a staff of 25 personnel, including 10 professionals, and is responsible to the vice president of technical services. Research work is concentrated in developing methods for preparation, dyeing or finishing new fiber or fabric textile products. Methods developed are then transferred to the quality control department where pilot tests for tensile strength, shrinkage, flammability, fading and other characteristics are made. Once tested, the research projects are transferred to the product development department for final development, design efforts, and pilot mill runs which precede product production at one of the firm's mills.

Ideas for new fibers, fabrics, finshes and production methods originate from a number of sources, the most important of which are the research laboratory, product development and design departments, corporate management, and the marketing group. These ideas or project proposals are presented by the directors of research, marketing and development departments at bi-annual corporate product development meetings for group evaluations. New projects selected are incorporated with the set of approved active projects and the six month corporate research and project development plan is finalized. Most projects have a short time horizon with the time from initiation of research to mill production typically being two years. The evaluation process normally includes consideration of approximately 30 new and existing textile and production method improvement projects. Formal, quantitative selection models are not being used as decision aiding tools.

The director of research was very interested in the proposed multistage, multiple objective model and gave indications that the thesis model is applicable in their planning processes. Project proposal data is available and includes estimates of technical success, cost data, and budget and personnel resources required. The decision tree format was viewed as a workable planning concept. Multiple goals for the research effort are definitely in existence and the model's capability for handling multiple criteria became a major selling point. Further, the firm's goals are considered in an ordinal type ranking and, during the course of the interview, the research director provided the following exmaple of the goal set:

Priority 1: Select those projects that are compatible with the firm's long range aggregate product run plans.

Priority 2: Select those projects that maximize the probability of technical successes.

Priority 3: Select those projects that minimize chemical input and manufacturing costs.

Priority 4: Select those projects that satisfy an urgency of need cirteria.

The research director noted that the priority structure changes over time and sensitivity analysis on various goal priorities is a required capability. It is also noted that the multiple goals represent an interesting situation since they are noncommensurate and conflicting in nature.

An additional area discussed for study within the model framework is the critical manpower shortage problem generated by the requirement placed on the research director to provide technical services to the firm's mills. Here, sensitivity analysis may be used to analyze "what if" questions concerning the research program that could be conducted if this task was transferred to another department or staff agency.

Model results would be used to demonstrate to top management the need to split-off technical services.

In summary, the research director was enthusiastic about application of the multiple objective model which is commensurate with his needs, and is a realistic conceptualization of the decision making process. As a result, an actual application of the thesis model was developed and is reported on in the final section of this chapter.

Case 2

The research laboratories of the pharmaceutical firm are principally engaged in exploratory research with regards to chemotherapy of microbial infections, antitumor agents, immunosuppressives, agents for cardiovascular disease and drug interactions. Other activities include pharmaceutical, agriculture medicine and veterinary medicine product support; and applied product research and development. Profits generated by products marketed by the pharmaceutical company are channelled back to the research laboratories and to the parent organization which supports other subsidiaries and medicine research. The interview was conducted with the director of research, development and medicine (RDM) administration of the research laboratories consisting of more than 700 personnel.

The R&D project selection decision is difficult to clearly define in this organization because of the concentration on exploratory research where the emphasis is centered on the advancement of medicine knowledge with no specific end product as the objective. However, since some of the exploratory research has generated marketable pharmaceutical products, it was of interest to further examine project evolution in these instances. Exploratory research is conducted in the organic chemistry department. Here, scientists study new compounds having desirable biological activity. Once synthesized, the compounds go to the pharmacology department where therapeutic usefulness is tested. The next step requires compound testing in the experimental therapy department. If promising, a research program is further defined into a project which is presented to a research committee by a project champion. The committee subjectively evaluates the proposal and makes a go/no go decision. If approved for further work, a project team is formed for product development in the medicine division and chemical development laboratories. There are approximately 30 development projects on going or under evaluation at any one time.

While it is not uncommon for research laboratories engaged in exploratory research to not use formal selection models for project selection nor gather quantitative data for proposal evaluation, the RDM administrator was nevertheless excited about the thesis model and requested that I repeat my presentation to a representative from the company's statistics department. Apparently the parent organization recently requested that all laboratories become involved in project accounting and budget planning; areas which have received no attention in past years. As a first step in response to this directive, the research committee implemented a simple scoring type model to evaluate technical success probabilities for development projects currently underway.

The RDM administrator indicated that the multiple objective model is feasible, useful and realistic for laboratories principally engaged in selection of development projects, but perhaps less useful for selection of exploratory research efforts. In this particular situation, it was noted that before a commitment is made to utilize the thesis model for development project selection and resource allocation, a commitment must be made to a data gathering and information system.

Case 3

The research laboratory of a government regulatory agency concentrates on applied in-house and contracted research programs to generate information concerning the health effects of a wide variety of chemicals and drugs for the development of environmental standards and control technology. The manager interviewed was the deputy director of the research laboratory employing approximately 350 professionals.

Although the deputy director showed interest in the multiple objective project selection model, he believed that the model is better suited for project termination rather than selection in their environment. The research laboratory supports a regulatory agency and, as such, the majority of the project selection decisions are mandated; that is, the project selection problem occurs outside of the laboratory. For example, when General Motors announced plans for widespread introduction of diesel powered passenger cars in the early 1980's, Congress passed a law directing the regulatory agency to develop emission standards and control technology. The research laboratory was given the task of discovering the health effects of various levels of atmospheric particulates. Although some latitude is available in selecting the major method used for the study, time and cost ruled out epidemology and clinical studies and, as a result, animal toxicology was selected as the only feasible study alternative. Even though a wide variety of animal toxicology studies are available, including bioassay, study of carcinogens, inhalent studies and skin painting, the method selection problem did not appear significant. Further, many of the mandated projects represent medium to long range time commitments. As such, the research portfolio for the next year includes the same projects being funded this year with no new proposals added to the portfolio.

Project termination, however, is distinctly the responsibility of the laboratory directors. For example, the research organization received a sizable budget cut during the course of a recent fiscal year. It followed that a number of projects had to be terminated before their completion in order to stay within the revised budget. The project directors were asked to rank order assigned projects. The laboratory directors then eliminated a set of the lowest priority projects with a research dollar amount equivalent to the budget cut. A subjective evaluation procedure was used for the termination decision, implicitly considering multiple objectives (one of the goals was to maintain in-house work and terminate contracted projects). It was noted that the thesis model is feasible for this situation as project priorities can be represented in benefit functions for one of the multiple goals and several model runs can be made to represent various funding levels.

The deputy director did indicate that the multiple objective model is feasible for research laboratories where selection decisions for research programs are made rather than mandated by higher authority. The example problem presented was useful in describing these types of realistic situations.

Case 4

The manager of the research division of a major consumer products company is responsible to the director of research and supervises a staff of 60 personnel, including 20 doctorates. The research division concentrates in applied research tied to development of new products and processes and, together with the analytical and science information divisions, works on chemical, physical and analytical studies of the firm's products. The research division also works closely with the development department, which is responsible for product and process development, and with the marketing research department. Although the industry is classified as one of low technology, the research and development activity is intense with over 530 personel, including 260 professionals (40 doctorates), actively engaged in R&D.

In the early 1970's, research project selection followed the general descriptive study as presented in Chapter I. Between 40 and 50 project proposals were generated each year and data profiles were carefully put together. Projects were selected using subjective evaluation processes taking into account the ranked multiple objectives identified in a corporate MBO plan. Currently, the research division has moved away from project selection as a result of implementation of a corporate wide performance management planning system which is operationalized in annual corporate working plans. All divisions, including research, identify key areas of concentration for the next year. The corporate planning department develops the annual plan from these areas, tying in the corporate goals and marketing strategies. The annual plan then becomes a working plan for research divisions. The working plan contains broad based funded areas of research as opposed to specific projects, and this constitutes fifty percent of the level of effort of the research staff. The remaining research capability is devoted to technical services support requirements and anticipatory research, where project selection is either mandated or otherwise inappropriate.

The research director, based on his previous experience with project selection schemes, viewed the proposed multiple objective model as feasible in organizations having formal project selection processes and noted that the consideration of multiple objectives and uncertainty were realistic characteristics. The director did state that under the former system of project selection, the multiple objective model could have been a workable decision aiding tool. At present, however, the model would be more useful for their analytical chemistry group where more defined selection and allocation decisions are made.

Case 5

The independent, not-for-profit research institute is engaged in basic and applied research in a wide variety of areas such as pharmacology, polymer science, environmental chemistry, biomedical engineering, atmospheric chemistry, and space systems. The total research staff numbers more than 400 professionals and 340 technicians and auxiliaries. The senior official interviewed was the Director of the Center for Applied Technology.

Research capability is maintained and expanded through revenue generated by research projects conducted for government, industry and foundation organizations on a contract basis. Approximately eighty percent of the research staff is allocated to this work. The remaining staff is allocated to program development which is a marketing function involved with finding clients for future research projects and developing contract proposals. Accordingly, in this unique research setting, project selection is accomplished by the clients and the organization attempts to match its capability with the needs of the clients. The only selection procedure envisioned by the center director, occurs at the annual meeting of the institute's vice presidents where areas of research concentration are identified through management consensus.

Although the multiple objective project selection model is not applicable for this institute, the center director, who has recently developed a project selection model for a government agency, gave an encouraging assessment and believed the model to be realistic and feasible for those research activities faced with the problem of project selection.

Summary of the Findings of the Interview Sessions

The survey of five organizations involved in R&D activities, which was carried out as part of this study, found agreement with the findings of other researchers that quantitative project selection models are not being used in the field. As noted in Chapter I, the most significant reason for this lack of application is failure of the model builders to account for realism with respect to multiple objectives, multiple stages in project evolution and uncertainty. However, three additional reasons were identified during the interview sessions. First, in the case of at least two of the firms, there is a lack of awareness of management science models proposed as decision aiding tools. Second, especially in the case of the pharmaceutical company, project proposal data is not collected at a level necessary for use of quantitative selection models. Third, in the case of the research institute and government agency, project selection occurs, to some extent, at the client or sponsoring activity level rather than within the research organization and the R&D activity responds with its capability. These and other findings concerning the potential for application of the multiple objective model are summarized in Table 5-9.

In summary, there was a high level of interest shown by all of the R&D managers and directors to the proposed model. A consensus opinion appeared to be that the multistage, multiple objective model is most applicable for those R&D activities concentrating on applied research or development projects which are associated with clearly defined end uses and where a certain degree of autonomy exists with regards to selecting the research portfolio. The capability to address multiple objectives, project evolution over the multistage horizon, and technical (internal) and outcome (external) uncertainty was judged a valid attempt to incorporate the realism of the research environment. The example problem illustrated through decision tree project planning and multiple objective formulations was received as representative of the type of situation occurring in the research

Table 5-9
Summary of Survey Findings

	Parent Organization Description	Field of R&D	Project Selection Process	Potential of Thesis Model
Case 1	Profit based textile mill	Applied research	Proposals presented and subjectively selected at bi-annual product development meetings.	High
Case 2	Pharmaceutical subsidiary	Exploratory research	Research committee subjectively evaluates proposals on a program by program basis.	Limited due to current data gaps and emphasis on exploratory research.
Case 3	Government regulatory agency	Applied research	Projects are selected by higher authority and other clients. Research lab responds with its capability.	High in project termination problem. None in selection problem.
Case 4	Profit based consumer products company	Product/process development and applied research	Research division specifies areas of research which are then summarized in an annual corporate working plan.	None in applied research. High in analytical chemistry division.
Case 5	Independent, not-for-profit research institute	Basic and applied research	Projects are selected by clients. Research activities respond with a capability on a contract basis.	None

activities faced with a selection problem. In summary, the multiple objective model appears to be a feasible approach which incorporates realistic characteristics of the selection process.

Application of the Thesis Model In A Corporate Setting

The fourth and final examination of the practical utility of the thesis model concerns an application involving R&D project selection and resource planning in the research department of a large textile firm. A general description of the research organization and the R&D decision making processes within this firm was provided in the summary of the interview sessions reported on pages 116-119. It was noted that the director of research was enthusiastic about incorporating the thesis model as a decision aiding tool for project selection and resource planning, and the results reported here represent the inaugural application.

The current problem of interest to the director of research concerns the selection of new research projects for the next four quarters of the planning horizon. An additional issue to be addressed as part of the selection problem concerns the shortage of professional staff available for research. Currently, the research director is responsible for providing the firm's textile mills with on-site technical support services. If this responsibility could be split-off to another department, or decentralized through an intensive training programming of staff personnel at the mill locations, more resources would be available resulting in the possible expansion of the portfolio of research projects. Thus, it was desired that the thesis model be used for the recommendation of two portfolios; one, given the departmental responsibility for providing technical services, and the other, considering the relief of this responsibility. In both cases, the portfolio is to be selected so as to best satisfy a set of miltiple objectives for the firm's research effort.

A detailed description of the problem begins with the project proposal decision trees shown in Figure 5-2. The critical and constraining resource, professional staff available for research, is shown at the bottom of the illustration for each of the four, three month planning periods, both with and without the technical support responsibility. Two main points are noted to clarify the numbers provided. First, the fluctuations in staff availability over the planning horizon result from the seasonal nature of product line development in the textile industry. During certain quarters of the year, some of the research staff is assigned to product line development activity which results in less staff available for research. In Figure 5-2, this additional activity is reflected in the first and fourth quarters. Second, it is shown that about half of the research staff is committed to technical support services, which is a commitment ratio based upon the most recent historical information. Thus, out of the eight or nine professionals available in the research department, depending on the quarter of the year, four are programmed for technical services. It was, however, indicated by the research director that general business conditions can effect this ratio; "when business is good, technical assistance declines; when business gets slack, the mills ask for more assistance with their problems." The decision trees also reflect the staff resources required for each project during each quarter and, in the case of projects B and E, the staff required for

Figure 5-2
Application 4: Project Trees

(1) Project		(2) Qtr 1 Staff Reqd	(3) Qtr 2 Staff Reqd	(4) Qtr 3 Staff Reqd	(5) Qtr 4 Staff Reqd	(6) Compatible with Development Plan	(7) Index of Success	(8) Cost Indices Chem. Input	(8) Cost Indices Mfg Process	(9) Urgently Needed
A		2	2	0	0	Yes	3	1	3	Yes
B	1	1	1	1	1	No	2	2	1	Yes
	2	1	1	1	1	No	1	2	1	Yes
	3	2	2	2	2	No	1	2	2	Yes
C		1	1	1	1	Yes	3	1	1	Yes
D		2	2	2	0	Yes	3	3	2	Yes
E	1	1	0	0	0	No	2	2	1	No
	2	1	1	0	0	No	2	2	1	No
	3	1	1	1	1	Yes	3	3	3	Yes
F		2	0	0	0	Yes	1	1	1	Yes
Staff Available with Tech Services		4	5	5	4					
Staff Available Without Tech Services		8	9	9	8					

each mutually exclusive project version.

Columns 6 through 9 of the decision trees provide information that link each of the proposed projects to the multiple objectives for the firm's research effort. Column 6 reflects whether or not the proposed project is compatible with long range product development plans. Column 7 provides a success index which ranges over the integers 1 through 3, where 1 indicates a low probability of success and 3 indicates a high probability. Column 8 includes the chemical input and manufacturing cost indices that also range over the integers 1 through 3, with 1 representing a low cost range and 3 a high cost range. Column 9 reflects whether or not a proposed project is urgently needed.[21]

Using the information and relationships provided in the decision trees, the next step involved the formulation of the zero-one goal programming models. Two models were developed for the initial analysis of the problem. Model I considers the case where technical services are the responsibility of the research department and Model II considers that technical services are not the department's responsibility. The multiple objectives and related constraint equations, which are given in Table 5-10, are described below. Unless specifically noted, each priority goal and constraint equation is common to the two models.

Priority 1: Ensure that only one of the mutually exclusive versions of projects B and E is selected if either or both of the projects is included in the final portfolio. As in other applications involving mutually exclusive system constraints, this goal must be satisfied to prevent the duplication of effort that would result by accepting two or more versions of the same project. This goal is satisfied by minimizing the positive deviational variables, p_1 and p_2, in rows 1 and 2 of Table 5-10.

Priority 2: Minimize overruns in staff requirements for the selected portfolios. For Model I, this goal is achieved by minimizing the positive deviational variables, p_3 through p_6, in rows 3-6. Note that each row represents one period in the planning horizon. For Model II, the goal is satisfied through minimization of p_7 through p_{10} in rows 7-10.

Priority 3: Select those projects that are compatible with the firm's long range product development plans. This goal is attained by minimizing p_{11} from a right hand side of zero in row 11.[22]

Priority 4: Maximize the index of technical successes. The constraint equation for this goal, shown in row 12, is formulated with a linear combination of project variables whose coefficients are taken from column 7 of Figure 5-2. By minimizing the negative deviational variable, n_{12}, from a large right hand side value, this goal can be attained since the zero-one goal program will attempt to select those projects having high probability of success indices.

Priority 5: Minimize chemical input and manufacturing process indices. The constraint equations for this goal, included in row 13 (chemical input costs) and row 14 (manufacturing process costs) involve a linear combination of the cost indices. By minimizing the positive deviational variables, p_{13} and p_{14}, from right hand side values of zero, this goal can be satisfied since the zero-one goal program attempts to select only those projects with low cost indices.

Table 5-10
Application 4: Model Constraints

						Variables							
Row No.	X_A	X_{B1}	X_{B2}	X_{B3}	X_C	X_D	X_{E1}	X_{E2}	X_{E3}	X_F	n_i	p_i	RHS
1		1	1	1							n_1	$-p_1 =$	1
2							1	1	1		n_2	$-p_2 =$	1
3	2	1	1	2	1	2	1	1	1	2	n_3	$-p_3 =$	4
4	2	1	1	2	1	2		1	1		n_4	$-p_4 =$	5
5		1	1	2	1	2			1		n_5	$-p_5 =$	5
6		1	1	2	1				1		n_6	$-p_6 =$	4
7	2	1	1	2	1	2	1	1	1	2	n_7	$-p_7 =$	8
8	2	1	1	2	1	2		1	1		n_8	$-p_8 =$	9
9		1	1	2	1	2			1		n_9	$-p_9 =$	9
10		1	1	2	1				1		n_{10}	$-p_{10} =$	8
11		1	1	1			1	1			n_{11}	$-p_{11} =$	0
12	3	2	1	1	3	3	2	2	3	1	n_{12}	$-p_{12} =$	15
13	1	2	2	2	1	3	2	2	3	1	n_{13}	$-p_{13} =$	0
14	3	1	1	2	1	2	1	1	3	1	n_{14}	$-p_{14} =$	0
15							1	1			n_{15}	$-p_{15} =$	0

Priority 6: Select those projects that satisfy an urgency of need criteria. This goal is attained by minimizing p_{15} in row 15.[23]

The objective functions for the two models are:

$$\text{Minimize } \bar{a} = \left[P_1(p_1+p_2);\ P_2(p_3+p_4+p_5+p_6);\ P_3(p_{11});\ P_4(n_{12});\ P_5(p_{13}+p_{14});\ P_6(p_{15})\right]. \tag{5.4}$$

$$\text{Minimize } \bar{a} = \left[P_1(p_1+p_2);\ P_2(p_7+p_8+p_9+p_{10});\ P_3(p_{11});\ P_4(n_{12});\ P_5(p_{13}+p_{14});\ P_6(p_{15})\right]. \tag{5.5}$$

The thesis model was used to solve the above problems and the results are reported in Table 5-11. Both models include a portfolio of projects that are compatible with the development plan (goal 3) and satisfy the urgency of need criteria (goal 6). For Model I (part of the staff assigned to technical services), three projects were selected that have high probabilities of success (goal 4). With the full staff available (Model II), two additional projects are added to the portfolio with the expected increase in the measure of success probabilities. Neither model resulted in the requirement for additional staff (achieving goal 2) but at the same time, it appears that there is an excessive amount of underutilization (six man-quarters of idle time for Model I and 14 man-quarters for Model II).

Because of the results concerning professional staff underutilization, it was of interest to rerun both models inserting a new third priority goal of minimizing the underutilization of the research staff in each quarter. This new goal is satisfied by minimizing the negative deviational variables in rows 3-6 of Table 5-10 for Model I, and minimizing the negative deviational variables in rows 7-10 for Model II. The objective function for the revised models, noted as Models IA and IIA, which now have seven priority goals (goals 3-6 for Models I and II become goals 4-7 for Models IA and IIA), are as follows:

$$\text{Model IA:} \quad \text{Minimize } \bar{a} = \Big[P_1(p_1+p_2);\ P_2(p_3+p_4+p_5+p_6); \qquad (5.6)$$

$$P_3(n_3+n_4+n_5+n_6);\ P_4(p_{11});$$

$$P_5(n_{12});\ P\ (p_{13}+p_{14});\ P_7(p_{15})\Big].$$

$$\text{Model IIA:} \quad \text{Minimize } \bar{a} = \Big[P_1(p_1+p_2);\ P_2(p_7+p_8+p_9+p_{10}); \qquad (5.7)$$

$$P_3(n_7+n_8+n_9+n_{10});\ P_4(p_{11});$$

$$P_5(n_{12});\ P_6(p_{13}+p_{14});\ P_7(p_{15})\Big].$$

The results of the runs of the thesis model are shown in Table 5-12. With the portfolios selected for the revised models, the staff under-utilization is significantly reduced (two man-quarters of idle time for Model IA and eight man-quarters of idle time for Model IIA). However, this reduction is at the expense of selecting one project (x_{B3}) which does not support the development plan goal for both Models IA and IIA, a portfolio of projects having a lower total index of success probabilities in the case of Model IA, and in the case of Model IIA, a portfolio having a higher index of costs.

The next step involved in this application was the performance of a sensitivity analysis on the priority goal structures. For Models I and II, which involved six prioritized goals, new problems were

Table 5-11
Application 4: Portfolios and
Goal Attainment Levels

	Model I	Model II
Projects Selected:	A,C,E3	A,C,D,E3,F
Goal 1: Avoid Duplication of Projects B and E:	Achieved	Achieved
Goal 2: Minimize Staff Overruns:	Achieved	Achieved
(The Staff Utilization is:)		
t=1	4	8
t=2	4	6
t=3	2	4
t=4	2	2
Goal 3: Development Plan Compatibility:	Achieved	Achieved
Goal 4: Maximize the Indices of Success[a]:	9	13
Goal 5: Minimize Cost Indices[a]:	12	19
Goal 6: Urgency of Need Criteria:	Achieved	Achieved

[a]Measured by the sum of the indices of the projects selected.

formulated by switching goal 4 (maximize the indices of success) with goal 3 (development plan compatibility). The solution to the Model I revised selection problem included the same portfolio as shown for Model I in Table 5-11. However, for Model II, the solution suggested a portfolio including projects A, B1, C, D and E3 which differed from that shown in Table 5-11. The associated goal attainment levels also changed, reflecting a reduction in the idle time of the research staff, a higher sum of the probability of success indices, higher cost indexes, and one project that does not support the development plan goal. Sensitivity analysis was also performed on the seven priority goal structures involved with Models IA and IIA. First, the probability of success goal was switched with the development plan compatibility goal and second, the goal involving minimization of costs was made a higher priority than the development plan compatibility and probability of success goals. The solutions to these formulations were identical to those of Table 5-12 for both models.

All of the above results, which were generated through the application of the thesis model, were presented to the director of research and the practical utility of the thesis model was discussed. Concerning the issue of practical utility, it was concluded that the thesis model appeared workable in the realistic R&D environment described. Multiple objectives, project data and resource constraints, and the interrelationships of these parameters, could be directly transformed into model formulations and computer program input parameters. Model output was easily interpreted and could be related to the selection problem as constructed by the director of research. Concerning the discussion of the model results, several important

Table 5-12
Application 4: Portfolios and
Goal Attainment Levels
(7 Goals)

	Model IA	Model IIA
Projects Selected:	B3,C,E3	A,B3,C,D,E3
Goal 1: Avoid Duplication of Projects B and E	Achieved	Achieved
Goal 2: Minimize Staff Overruns:	Achieved	Achieved
Goal 3: Minimize Staff Under-utilization. The under utilization is:		
t=1	0	0
t=2	1	1
t=3	1	3
t=4	0	4
Goal 4: Development Plan Compatibility:	Not Achieved (B3 Selected)	Not Achieved (B3 Selected)
Goal 5: Maximize the Indices of Success[a]:	7	13
Goal 6: Minimize Cost Indices[a]:	12	21
Goal 7: Urgency of Need Criteria:	Achieved	Achieved

[a]Measured by the sum of the indices of the projects selected.

conclusions were reached. Specifically, the responsibility of providing technical services has a direct impact on the research mission of the department. Here, the model was useful in not only identifying the obvious result that more research can be conducted with the full staff available, but also in illustrating the magnitude of change in the attainment of the research department's goals when the resource constraint is adjusted towards the full staff level. Further, the sensitivity analysis provided by changing goal priorities and adding goals was useful in the identification of dominant projects (i.e., those projects which consistently appeared in each portfolio generated). Here, the model was judged to be of benefit to the decision maker by reducing the subset of projects that require further management analysis for the selection decision. In a more general sense, the discussion of the results provided a vehicle by which the research director and the author could speak more directly and with more insight, about goal articulation and the project selection decision process within the firm. Both the research director and the author concluded that this focused discussion was valuable in understanding what was actually happening within the firm and what was desired.

In summary, the thesis model appeared to be a workable decision aiding tool for a R&D project selection problem in a corporate setting. It was particularly encouraging that the research director expressed an interest and made arrangements for additional work using the thesis model.

Footnotes

[1]Validity refers to the degree of similarity between model results and other reported good solutions, or the optimal solution when known.

[2]W. E. Souder, "Optimum Research and Development Models" (Ph.D. Dissertation, St. Louis University, 1970).

[3]T. Mandakovic, "An Interactive Model for R&D Project Selection Decision Making in Hierarchical Organizations" (Ph.D. Dissertation, University of Pittsburg, 1978).

[4]Aside from being the most recent technique available, Mandakovic developed his integer (zero-one) programming algorithm under the tutalage of W. Souder, perhaps the recognized authority in the field of R&D project selection problem modeling and applications. Further, Mandakovic's research includes algorithm validity tests using actual problem data. Thus, it provides a benchmark for comparison with the present research model.

[5]S. Senju, and Y. Toyoda, "An Approach to Linear Programming with 0-1 Variables," Management Science, Vol. 15 (December, 1968), pp. B196-B207.

[6]Y. Toyoda, "A Simplified Algorithm for Obtaining Approximate Solutions to Zero-One Programming Problems," Management Science, Vol. 21 (August, 1975), pp. 1417-1427.

[7]Mandakovic solved several 1,000 variable problems in CPU times ranging from 203 to 310 seconds on a PDP-10 computer system, and even solved a 10,000 variable problem and reported that the model performed efficiently. Solution validity, however, was not tested for these problems since the optimum solutions were unknown (see Mandakovic, pp. 199-200).

[8]Souder, Appendix VII.

[9]Mandakovic, p. 197.

[10]Mandakovic, pp. 139-149. Note that multiple time period resource constraints are handled by the Mandakovic algorithm and computer code, although technical outcome uncertainty between periods is not directly addressed.

[11]W. E. Souder, "Analytical Effectiveness of Mathematical Models for R&D Project Selection," Management Science, Vol. 19 (April, 1973), pp. 907-923.

[12]Mandakovic, p. 197.

[13] Ibid., p. 198.

[14] E. M. Rosen, and W. E. Souder, "A Method for Allocating R&D Expenditures," IEEE Transactions on Engineering Management, Vol. EM-12 (September, 1965), pp. 87-93.

[15] The original problem included 8 projects, a 6 year planning horizon and up to 33 funding levels for each project in each year which resulted in 850 project versions to be examined in the selection problem. Further, 150 problems were solved by varying the first year budget constraint from $ 0 to $ 1,500,000 in increments of $10,000. For the application reported in this chapter, the major changes included providing two funding levels for each project (rather than up to 33) and dropping out two projects. Without these changes, the problem was too large for the thesis model.

[16] The probabilities associated with the two funding levels shown in Table 5-5 were those probabilities and funding levels in the optimum solution reported by Rosen and Souder and were therefore chosen for comparison purposes.

[17] In the original problem reported by Rosen and Souder, the total expected output goal was established as 15. This figure was reduced to 6.6 by deducting the total expected output values for the two projects dropped for this application.

[18] This goal was established as 55 in the original problem but was reduced to 45 for this application to account for the changes in return on expenditure resulting from dropping out two projects.

[19] A. J. Keown, B. W. Taylor III, and C. P. Duncan, "A Zero-One Goal Programming Approach to R&D Project Selection," Presented at the American Institute of Decision Sciences National Meeting, St. Louis, Mo., October-November, 1978.

[20] R. L. Morris, "Integer Goal Programming: Methods, Computations, Applications" (Ph.D. Dissertation, Virginia Polytechnic Institute and State University, 1976), pp. 61-71.

[21] Because of the proprietary nature of the information associated with this application, the textile firm elected not to release actual project descriptions and, in some cases, the actual data parameter estimates (i.e., cost input and probability of success parameters). Accordingly, a scaling process was used for the cost data and probabilities of success which allowed the transmittal of the otherwise sensitive information while at the same time preserved the cardinal scale relationships of the parameters. The resultant data format did not detract from the project selection and resource planning problem at hand; in fact, the general usefulness of the model was demonstrated in that it was shown to be capable of handling a wide variety of data parameters.

[22] An alternate formulation would be to minimize the negative deviational variable in a constraint equation containing a linear combination of those projects which are compatible with the product development plan and having a large right hand side value. Both formulations represent the objective statement in that the zero-one goal programming model attempts to select compatible projects and not select the incompatible ones. However, the formulation shown in Table 5-10 permits a more direct interpretation of the program output.

[23] As with the constraint equation developed for the priority 3 goal, there are two possible formulations. The alternate constraint equation would be a linear combination of projects that satisfy an urgency of need criteria with the goal being to minimize the negative deviational variable from a large right hand side value.

CHAPTER VI

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

A multiperiod, stochastic, multiple objective, zero-one mathematical programming model has been presented for the research and development project selection and resource allocation problem. Each feature of the complete model has been designed to incorporate realistic aspects of the R&D decision making process, thereby establishing a contribution to the practical and theoretical state-of-the-art in R&D project selection modeling. In the preceeding chapters, the model has been demonstrated to be capable of:

1) Selecting from a set of potential research and development projects a portfolio that maximizes the attainment of multiple, noncommensurate objectives using a goal programming format.
2) Incorporating the multistage and sequential decision making nature of R&D projects and representing project interactions and interrelationships through decision tree planning techniques.
3) Addressing the limitations of scarce multiple resource constraints.
4) Representing mutually exclusive and mutually dependent projects or versions.

5) Incorporating discrete probability estimates or probability distributions for the various parameter estimates using simulation techniques.

6) Providing good solutions to medium scale problems in relatively fast computer code processing times, thus providing model users the benefit of low cost multiple runs for sensitivity analysis in conjunction with planned changes in input parameters.

The model was successfully tested against recent mathematical programming techniques also designed for the R&D project selection problem. Comparable, and in some cases, superior results were obtained in all of these tests, and the added capabilities of the thesis model were discussed and are summarized in Table 6-1. In addition, an appraisal of model feasibility was gained through an actual application and through presentations to R&D laboratory directors and administrators.

A Summary of the Application of the Thesis Model in the R&D Project Selection Environment

The multistage, multiple objective project selection and resource allocation model, presented herein, is designed and intended for those R&D activities which enjoy a certain degree of autonomy with regards to selecting the research portfolio, and that concentrate efforts on applied research or development projects associated with clearly defined end uses. On the basis of the many applications of the thesis model carried out as part of this research, the following sequence of activities for its use by a practicing R&D manager is suggested.

The first step in any application of the model is the development of the project trees which provide the input data for the goal programming formulation. Project or decision trees, which are unique to the particular organizational environment, afford decision makers the benefits of detailed project planning and visual recognition of project and constraint interrelationships and technical outcome uncertainty.

The next step is the selection of dominant future outcome states through forced choice chance node selection or simulation techniques. Alternatively, for small problems with a manageable number of chance nodes, all outcome states can be accounted for through a stochastic representation as was illustrated in the example problem presented in Chapter III.

The third step in model application involves the zero-one goal programming formulation. This step includes the prioritization of the multiple objectives and development of system and goal constraints using input data from the project trees in order to operationalize the objectives. Following this step, the zero-one goal programming algorithm is used to select a portfolio that best satisfies the set of multiple objectives. Table 6-2 provides guidelines for using the different versions of the algorithm depending upon the size of the problem.

Finally, in those situations where model users are interested in examining various strategies associated with changes in the priority structure, resource constraint levels, or technical outcome states, multiple model runs were suggested for sensitivity analysis purposes.

Table 6-1
Model Capability Comparisons

	Multiple Objectives	Multiple Constraints	Multiple Time Periods with Outcome Uncertainty	Problem Size (Project Variables) Small[a]	Medium[b]	Large[c]
Thesis Model	X	X	X	X	X	
Zero-One Model (Mandakovic, 1978)		X			X	X
Dynamic Programming Model (Rosen and Souder, 1965)			X	X	X	X
Goal Programming Model (Keown, Taylor and Duncan, 1978)	X	X		X		

[a] Up to 20 project variables

[b] Between 20 and 100 project variables

[c] More than 100 project variables

Table 6-2
Suggestions for Use of the
Goal Programming Algorithm Versions

Case	Decision
1. If there are less than 45 project variables:	Use the variable selection and exchange heuristics with full partitioning.
2. If there are between 45 and 75 project variables:	Use the variable selection and exchange heuristics for intital solution. In a subsequent run, partition on those variables selected in the initial solution.
3. If there are between 75 and 100 project variables:	Use the variable selection and exchange heuristics without partitioning.
4. If there are more than 100 project variables with clearly defined divisions or levels providing up to 100 variables as their input:	Formulate divisional subproblems and use the appropriate version as described in the above cases.
5. If there are more than 100 project variables with no disaggregation by division possible:	a. Use the variable selection heuristic with or without partitioning. b. Alternatively, extract from the original problem, a problem of tractable size and use the appropriate version from cases 1 through 3 above. This procedure has been followed in other applications involving different models (see, for example, Chiu and Gear[1]).

Multiple runs may also be required for statistical analysis if external parameters such as the probabilities of commercial success or expected profits are input as probability distributions.

Suggestions for Further Research

Direction of Future Research in the R&D Decision Making Environment

In a recent publication which appeared after the present research was well underway, W. Souder, the current Chairman of the TIMS College of R&D Management and Director of the Technology Management Studies Group at the University of Pittsburg, wrote the following assessment of R&D project selection models and the real world environment for which they are designed:[2]

> Most models appear to be constructed largely for the single decision maker, rather than for organizational decision making... the real world complexities of multiple objectives and constraints are usually glossed over, and the models are formulated around single objectives and single constraints... Management science models reflect only the analytical aspects of project evaluation. But in real world project evaluation, decisions are often profoundly influenced by a multitude of organizational and human behavioral factors...
>
> Three important organizational behavioral needs must be satisfied before any project evaluation model can be used effectively. First of all, organizational goals and constraints at all levels of the organization must be clearly-defined and agreed upon. They are the ultimate standards for killing some projects and accepting others.
>
> Second, most project evaluation data are necessarily subjective in nature. Unless a spirit of trust and openness is felt by the parties, it is not likely that such data will be fully and openly exchanged.
>
> Third, for successful project evaluation a minimum level of personal awareness is needed.

The present research found a high degree of consensus with these observations and, indeed, the thesis model was specifically designed with the capability to handle the real world complexities of multiple objectives, multiple constraints, and uncertainty in data parameters and future outcome events. Possessing these capabilities, the thesis model was proposed as a decision aiding tool with practical utility in the total R&D decision making process which was earlier illustrated and described in Figure 1-1 of the introductory chapter. However, it is recognized that the model is only a part of the process and the direction for future research must be in the upstream decision stages where the model inputs are developed. That is, research must now concentrate on means of defining multiple objectives, developing accurate estimates of organizational resources and needs, generating future event scenarios and project proposal data based on factual information exchanges, and methods of achieving consensus on these items, so that, in interaction with the thesis model, an effective total structured process is designed.

Nominal group processes with psychometric Q-Sort or pairwise comparison experiments (discussed in Chapter II) represent a start in this area, especially for generation of the set of multiple research goals. It remains to test the practical utility of a total structured process through an application involving Q-Sort type experiments for generation of input data for the thesis model and feedback of output information to the decision making entities. Follow-up analysis would be required to determine if such a total process is of enhanced utility to R&D managers in their determination of a portfolio for research in their organization.

Other Applications and Extensions of the Multiple Objective Model

The thesis model was particularly designed for the special characteristics of the R&D project selection decision making process. However, since the R&D project selection problem is a special case of the more general class of resource allocation problems and since the thesis model expands the capability of existing multiple objective integer goal programming algorithms, there exists a potential for applications involving other multicriteria problem situations where the decision variables represent "go-no go" decisions. The zero-base budgeting problem (see, for example, Pyhrr[3] and Cheek[4]) is an excellent example of this type of problem. Here, top management determines goals for organizational units and establishes expenditure guidelines for the budget year. Operating management develops alternative activity plans or decision packages for achieving the operational objectives and determines their expenditure requirements. The thesis model is suggested as an interactive decision aiding tool to assist the organization in determining which of the activity plans should be funded in order to achieve the objectives and stay within the established expenditure levels. The model's capability to analyze various future event scenarios would enhance its application in zero-base budgeting decision making. Similarly, the capital budgeting problem under capital rationing suggests another environment for application of the thesis model.

Another area for model application was identified in the interview with the director of the Center for Applied Technology in the nonprofit research institute. There, the problem of interest was scientific staff resource allocation which is more generally defined as the capacity management problem in knowledge intensive organizations. For this particular organization, the laboratory directors must periodically determine the allocation of staff members to three areas: proposal development; marketing of proposals to prospective clients; and contract work on proposals selected by the clients. In this case, the zero-one goal programming model can be used by considering subunits of areas as zero-one decision variables having different payoffs and resource utilization rates.

Another direction for future research concerns the zero-one goal programming algorithm developed as the solution technique for the multiple objective model formulations. The heuristics developed represent several approaches to solving medium scale problems. Research in development of other techniques that further expand the model's capability and improve its efficiency would enhance the model's potential for application in multiple objective problem formulations having ordinally ranked, noncommensurate goals.

Footnotes

[1]L. Chiu and A. E. Gear, "An Application and Case History of a Dynamic R&D Portfolio Selection Model," IEEE Transactions on Engineering Management, Vol. EM-26 (February, 1979), pp. 2-7.

[2]W. E. Souder, "A System for Using R&D Project Evaluation Methods," Research Management, Vol. 21 (September, 1978), pp. 29-37.

[3]P. A. Pyhrr, Zero-Base Budgeting: A Practical Management Tool for Evaluating Expenses (New York: John Wiley & Sons, Inc., 1973).

[4]L. M. Cheek, Zero-Base Budgeting Comes of Age: What It Is and What Makes It Work (New York: AMACOM, 1977).

APPENDIX A

Description of the Computer Code and Data Preparation for the Zero-One Goal Programming Algorithm

1. General Description

   a. This program is written in Fortran IV and includes variable selection, exchange and partition heuristics for the zero-one goal programming problem.

   b. Restrictions

      1) Only zero-one variables are permitted.

      2) System constraints are not allowed as such. If any exist, convert them to goal constraints by minimizing the deviational variables involved at the first priority level.

      3) Only one deviational variable of a constraint equation may be minimized in a problem. If both deviational variables are to be minimized, generate two constraints and minimize the positive (negative) deviational variable in the first constraint and the negative (positive) deviational variable in the second.

      4) Negative technological coefficients in the goal constraint equations are not allowed. If any exist, replace the respective variables with complementary variables and add the appropriate number of equality constraints to achieve the complementarity. For example, if the coefficient of x_1 in one of the goal constraints is -1, replace x_1 with $(1 - x_1')$ and add the system constraint $x_1 + x_1' = 1$.

   c. Output for this program includes input data checks, the variables selected in the best solution and the goal underattainment levels of the best solution.

d. The dimensions for the number of constraints, decision variables, and priority levels in the computer code listed in Appendix B are:

1) NROW, the number of constraints (1 ≤ NROW ≤ 40).

2) NVAR, the number of variables (1 ≤ NVAR ≤ 100).

3) NPRI, the number of priority levels (1 ≤ NPRI ≤ 10).

2. Data Preparation

a. Dimension Card

Col. 5 - 7	(I3)	The number of constraints.
Col. 8 - 10	(I3)	The number of variables.
Col. 11 - 13	(I3)	The number of priorities.

b. Objective Function Cards

Col. 1	(I1)	"1" if the positive deviation is to be minimized, "2" if the negative deviation is to be minimized.
Col. 5 - 9	(I5)	The row in which the deviational variable appeared.
Col. 10 - 14	(I5)	The priority level at which the deviational variable is to be minimized.
Col. 15 - 25	(F11.0)	The differential weighting factor of the deviational variables. If the factor is 1.0, it must be punched.

Note: Objective function cards should be input in increasing order by row numbers (card for row 1 is first, row 2 is second, etc.)

c. Technological Coefficients Cards

Col. 5 - 9	(I5)	The row in which the coefficient appears.
Col. 10 - 14	(I5)	The column in which the coefficient appears.
Col. 15 - 25	(F11.0)	The coefficient's value.

Note: Punch one card for each nonzero coefficient. The program assigns a value of 0.0 for any coefficient not specified. After the last coefficient card, include a trailer card with "999" in columns 7 - 9.

d. Right Hand Side Value Cards

Col. 1 - 10	(F10.0)	The right hand side value of the first constraint.
. . .		. . .
Col. 71 - 81	(F10.0)	The right hand side value of the eighth constraint.

Note: If there are more than eight constraint rows, continue on the next card(s) with the same format.

d. Option Card

Col. 1 - 3	(I3)	"1" if the variable selection routine is to be used; "2" if both the variable selection and exchange routines are to be used.

e. Partitioned Subproblems Dimension Card

Col. 1 - 3	(I3)	The number of partition subproblems to be solved. If none, punch "1" (this indicates use of only the selection and exchange heuristics).

f. Partitioned Subproblem Cards (one set of cards for each partitioned subproblem)

Col. 1 - 2	(I2)	"1" if the first variable is considered for solution; "Ø" if the first variable is forced out of solution.
. . .		. . .
Col. 79 - 80	(I2)	"1" if the 40th variable is considered for solution; "Ø" if the 40th variable is forced out of solution.

Note: If there are more than 40 variables, continue on the next card(s), using the same format. If no partitioned subproblems are to be solved, include one set of partitioned subproblem cards with each variable having a value of 1.

3. Additional Features and Suggestions for Use of the Program Options.

a. Write statements, enclosed in comment cards, are contained throughout the program. These statements will provide interim results after each variable selection procedure; after each iteration of the variable exchange routine; and at the completion of each partitioned subproblem procedure. To obtain these interim results, repunch the appropriate write statements without the comment "C" entry in card columns 1 and 76. Format statements are included.

b. The program is currently written to solve one problem (including one or more partitioned subproblems) at a time. However, problem stacking is easily accomplished by changing the counter control statement "IF(IEND.LT.1) GO TO 1000" (Fortran statement number 292) to indicate the number of stacked problems. For example, if three complete problems are to be solved in one batch program submission, the counter control statement should read "IF(IEND.LT.3)GO TO 1000". Note that each stacked problem must include all of the data cards described in paragraph 2 above, even if there is some replication.

c. The partitioning procedure was designed specifically for the general class of zero-one variable selection problems having mutually exclusive system constraints, i.e., select either version 1 or 2 of project 1, but not both so as to avoid project duplication. In the above example, two partitioned subproblems can be solved; one with the version 1 decision variable forced out of solution and the other with version 2 forced out. However, the procedure is general and any variable(s) can be selectively forced out of the solution procedure.

d. The program has been tested on a variety of problems ranging from 3 to 10 priorities, 15 to 62 constraint rows, and 6 to 180 zero-one decision variables. Although CPU times will vary depending upon the structure of the problem and the particular computer system available, the following suggestions are made for using the program options if running time is a consideration.

1) If there are less than 45 zero-one decision variables: use the variable selection and variable exchange option with as many partitioned subproblems as dictated by the mutually exclusive variable system constraints and/or as desired.

2) If there are between 45 and 75 decision variables: use the variable selection and exchange option for an initial solution. If desired, partition on the solution variables in a subsequent run.

3) If there are between 75 and 100 decision variables: use the variable selection and exchange option.

4) If there are more than 100 variables: use the variable selection option. The partitioning procedure may also be employed with this option. Note that the array dimensions in the program must be changed if there are more than 100 variables.

APPENDIX B

Computer Code for the Zero-One Goal Programming Algorithm

```
      COMMON MINDEV(40), IVLPRI(40), WTDEV(40), COEF(40,100), RHS(40)
      COMMON SUM(10,100), X1(100), X2(100), UNDER(10), UMIN(10)
      COMMON COMEAR(10), POSDEV(40), DEVNEG(40), NROW, NVAR, NPRI, II
      COMMON HOLD(10), HOLDX2(100), BESTX2(100), HOLDU(10), BESTU(10)
      COMMON TEMPU(10), HOLDX1(100), BESTX1(100), TEMPX1(100)
      COMMON TEMPX2(100), SWAPX1(100), SWAPX2(100), SUPRX1(100)
      COMMON SUPRX2(100), SWAPU(10), SUPRU(10), NROWS(40)
      COMMON NPROBM(100), SMALLU(10), SMLSTU(10), FINIX2(100)
      IEND=0
 1000 CONTINUE
C        READ IN AND PRINT OUT NUMBER OF ROWS (NROW), VARIABLES (VAR),      C
C        AND GOAL PRIORITY LEVELS (NPRI).                                   C
      READ(1,1)NROW,NVAR,NPRI
      WRITE(3,900)NROW
      WRITE(3,901)NVAR
      WRITE(3,902)NPRI
      DO 20 I=1,NROW
      MINDEV(I)=0
      NROWS(I)=0
      LVLPRI(I)=0
      WTDEV(I)=0.0
      RHS(I)=0.0
      DO 10 J=1,NVAR
      COEF(I,J)=0.0
   10 CONTINUE
   20 CONTINUE
      DO 25 I=1,NPRI
      DO 24 J=1,NVAR
      SUM(I,J)=0.0
   24 CONTINUE
   25 CONTINUE
      WRITE(3,905)
      WRITE(3,906)
C        READ IN AND PRINT OUT FOR EACH ROW: THE DEVIATIONAL VARIABLE       C
C        TO BE MINIMIZED (MINDEV), ROW NUMBER (NROWS), PRIORITY LEVEL       C
C        (LVLPRI), AND THE WEIGHTING FACTOR (WTDEV).                        C
      READ(1,2)(MINDEV(I),NROWS(I),LVLPRI(I),WTDEV(I),I=1,NROW)
      WRITE(3,907)(MINDEV(I),NROWS(I),LVLPRI(I),WTDEV(I),I=1,NROW)
      WRITE(3,910)
C        READ IN THE TECHNOLOGICAL COEFFICIENTS (COEF), ADJUST FOR          C
C        WEIGHTING FACTORS, AND PRINT OUT.                                  C
   30 READ(1,3)IROW,ICOL,VALUE
      IF(IROW.EQ.999)GO TO 40
      COEF(IROW,ICOL)=VALUE*WTDEV(IROW)
      WRITE(3,911)IROW,ICOL,COEF(IROW,ICOL)
      GO TO 30
```

```
C           READ IN THE RIGHT HAND SIDE VALUES (RHS), ADJUST FOR WEIGHTING       C
C           FACTORS AND PRINT OUT.                                                C
   40    READ(1,4) (RHS(I),I=1,NROW)
         WRITE(3,915)
         DO 50 I=1,NROW
         RHS(I)=RHS(I)*WTDEV(I)
         WRITE(3,916)RHS(I)
   50    CONTINUE
C           COMPUTE MATRIX OF COEFFICIENTS (SUM) FOR THE VARIABLE SELECTION      C
C           ROUTINE AND PRINT OUT.                                                C
         DO 80 K=1,NROW
         J=LVLPRI(K)
         IF(MINDEV(K).NE.2)GO TO 80
         DO 70 L=1,NVAR
         SUM(J,L)=SUM(J,L)+COEF(K,L)
   70    CONTINUE
   80    CONTINUE
         WRITE(3,920)
         DO 90 I=1,NPRI
         WRITE(3,921) (SUM(I,J),J=1,NVAR)
   90    CONTINUE
C           READ IVERSN WHICH IS INPUT AS "1" TO INDICATE THAT ONLY THE          C
C           VARIABLE SELECTION ROUTINE IS TO BE USE4, OR AS "2" TO INDICATE      C
C           THAT BOTH THE SELECTION AND EXCHANGE ROUTINES WILL BE USED.          C
         READ(1,5)IVERSN
C           BEGIN THE PARTITION ROUTINE                                           C
C                  READ IN AND PRINT OUT THE NUMBER OF FORCED START PROBLEMS     C
C                  AND SET OF FREE VARIABLES ASSOCIATED WITH EACH, THEN START    C
C                  THE PARTITION ROUTINE.                                         C
         DO 100 I=1,NPRI
         SMLSTU(I)=10.0
         SMALLU(I)=0.0
  100    CONTINUE
         DO 110 I=1,NVAR
         FINLX2(I)=0.0
         NPROBM(I)=0
  110    CONTINUE
         READ(1,5)NPROB
         WRITE(3,940) NPROB
         JJJJJ=0
         DO 899 N3=1,NPROB
  120    WRITE(3,943) N3
         WRITE(3,941)
         READ(1,6) (NPROBM(N1),N1=1,NVAR)
         WRITE(3,942) (NPROBM(N1),N1=1,NVAR)
```

```
      DO 140 I=1,NVAR
      X1(I)=1.0
      X2(I)=0.0
      HOLDX1(I)=0.0
      HOLDX2(I)=0.0
      TEMPX1(I)=0.0
      TEMPX2(I)=0.0
      BESTX1(I)=0.0
      BESTX2(I)=0.0
      SWAPX1(I)=0.0
      SWAPX2(I)=0.0
      SUPRX1(I)=0.0
      SUPRX2(I)=0.0
140   CONTINUE
      DO 150 I=1,NPRI
      UNDEF(I)=0.0
      UMIN(I)=0.0
      COMPAR(I)=0.0
      HOLD(I)=0.0
      HOLDU(I)=0.0
      TEMPU(I)=0.0

      BESTU(I)=0.0
      SWAPU(I)=0.0
      SUPRU(I)=0.0
150   CONTINUE
      K1=0
      K4=0
      I7=0
      III=NPRI
      IIIII=0
      DO 210 II=1,NPRI
      CALL USET
      UNDEF(II)=UMIN(II)
210   CONTINUE
      GO TO 500
220   CONTINUE
C        VARIABLE SELECTION ROUTINE.                                   C
C              MAKE ONE PASS THRU SET OF FREE VARIABLES (X1) AND SELECT C
C              VARIABLES FOR SOLUTION (X2) THAT MINIMZE DEVIATIONS FROM C
C              HIGHER TO LOWER PRIORITY GOALS.                         C
      I1=0
230   I1=I1+1
      IF(I1.LE.NPRI)GO TO 235
      DO 234 M=1,NVAR
      IF(X2(M).EQ.0.0)X1(M)=1.0
234   CONTINUE
```

```
      IF(IVERSN.EQ.1)GO TO 996
      GO TO 300
235   IN=0
      BIGN=0.0
      IF(UNDER(I1).EQ.0.0)GO TO 230
      DO 240 I2=1,NVAR
      IF(NPROEM(I2).EQ.0)GO TO 240
      IF(X2(I2).EQ.1.0)GO TO 240
      IF(X1(I2).EQ.0.0)GO TO 240
      IF(SUM(I1,I2).LE.BIGN)GO TO 240
      BIGN=SUM(I1,I2)
      IN=I2
240   CONTINUE
      IF(IN.EQ.0)GO TO 230
      X2(IN)=1.0
      X1(IN)=0.0
      II=I1
      IJ=I1
      IBYE=0
      CALL USET
      COMPAR(II)=UMIN(II)
      IF(UNDER(II)-COMPAR(II))241,250,245
241   X2(IN)=0.0
      GO TO 235
245   DO 247 II=1,NPFI
      CALL USET
      COMPAR(II)=UMIN(II)
      IF(II.GE.IJ)GO TO 246
      IF(COMPAR(II).LE.UNDER(II))GO TO 246
      X2(IN)=0.0
      GO TO 235
246   HOLD(II)=COMPAR(II)
247   CONTINUE
      GO TO 256
250   DO 255 II=1,NPFI
      CALL USET
      COMPAR(II)=UMIN(II)
      IF(IBYE.EQ.1)GO TO 254
      IF(II.GT.IJ)GO TO 252
      IF(COMPAR(II).LE.UNDER(II))GO TO 254
251   X2(IN)=0.0
      GO TO 235
252   IF(UNDER(II)-COMPAR(II))251,254,253
253   IBYE=1
```

```
 254   HOLD(II)=COMEAF(II)
 255   CONTINUE
 256   CONTINUE
       DO 260 J1=1,NPRI
       UNDER(J1)=HOLD(J1)
 260   CONTINUE
 500   IIIII=IIIII+1
       JJJJJ=JJJJJ+1
       GO TO 220
C          BEGIN BEST SWAP 1 X 1 HEURISTIC                                    C
C                DETERMINE IF BETTER SOLUTIONS CAN BE OBTAINED BY REMOVING    C
C                ONE VARIABLE, ITERATIVELY, FROM X2.   IF SO, TAKE BEST       C
C                SOLUTION AND REPEAT THE SWAP PROCEDURE.                      C
 300   K1=K1+1
       IF(K1.GT.1)GO TO 350
C      WRITE(3,932)                            (THIS STMT PRINTS INTERIM RESULTS)    C
       DO 310 K2=1,NVAR
       HOLDX1(K2)=X1(K2)
       HOLDX2(K2)=X2(K2)
       BESTX1(K2)=HOLDX1(K2)
       BESTX2(K2)=HOLDX2(K2)
       TEMPX1(K2)=HOLDX1(K2)
       TEMPX2(K2)=HOLDX2(K2)
       SUPRX1(K2)=HOLDX1(K2)
       SUPRX2(K2)=HOLDX2(K2)
       IIX2=BESTX2(K2)
C      WRITE(3,933)K2,IIX2                     (THIS STMT PRINTS INTERIM RESULTS)    C
 310   CONTINUE
C      WRITE(3,934)                            (THIS STMT PRINTS INTERIM RESULTS)    C
       DO 320 K3=1,NPRI
       HOLDU(K3)=UNDER(K3)
       BESTU(K3)=HOLDU(K3)
       SUPRU(K3)=HOLDU(K3)
C      WRITE(3,935)K3,BESTU(K3)                (THIS STMT PRINTS INTERIM RESULTS)    C
 320   CONTINUE
 330   K4=K4+1
       IF(TEMPX2(K4).EQ.0.0)GO TO 330
       IF(K4.GT.NVAR)GO TO 600
       TEMPX2(K4)=0.0
       TEMPX1(K4)=0.0
       DO 335 K5=1,NVAR
       X2(K5)=TEMPX2(K5)
       X1(K5)=TEMPX1(K5)
```

```
  335 CONTINUE
      DO 340 II=1,NPRI
      CALL USET
      TEMPU(II)=UMIN(II)
  340 CONTINUE
      DO 345 K6=1,NPRI
      UNDER(K6)=TEMPU(K6)
  345 CONTINUE
      GO TO 220
  350 DO 360 K7=1,NPRI
      IF(K7.EQ.III.AND.UNDER(K7).EQ.BESTU(K7))GO TO 370
      IF(UNDER(K7).LT.BESTU(K7))GO TO 390
      IF(UNDER(K7).EQ.BESTU(K7))GO TO 360
      GO TO 370
  360 CONTINUE
  370 DO 380 K8=1,NVAR
      TEMPX2(K8)=BESTX2(K8)
      TEMPX1(K8)=BESTX1(K8)
  380 CONTINUE
      GO TO 330
  390 L7=1
      DO 400 L1=1,NPRI
      IF(L1.EQ.III.AND.UNDER(L1).EQ.SUPRU(L1))GO TO 370
      IF(UNDER(L1).LT.SUPRU(L1))GO TO 410
      IF(UNDER(L1).EQ.SUPRU(L1))GO TO 400
      GO TO 370
  400 CONTINUE
  410 DO 420 L2=1,NPRI
      SWAPU(L2)=UNDER(L2)
      SUPRU(L2)=SWAPU(L2)
  420 CONTINUE
      DO 430 L3=1,NVAR
      SWAPX1(L3)=X1(L3)
      SWAPX2(L3)=X2(L3)
      SUPRX1(L3)=SWAPX1(L3)
      SUPRX2(L3)=SWAPX2(L3)
  430 CONTINUE
      GO TO 370
  600 IF(L7.EQ.0)GO TO 800
      DO 440 L4=1,NVAR
      X1(L4)=SUPRX1(L4)
      X2(L4)=SUPRX2(L4)
  440 CONTINUE
      DO 450 L5=1,NPRI
      UNDER(L5)=SUPRU(L5)
```

```
  450 CONTINUE
      K1=0
      K4=0
      L7=0
      GC TC 300
  800 CONTINUE
C     WRITE(3,936)                          (THIS STMT PRINTS INTERIM RESULTS)    C
      DO 810 I=1,NVAR
      IX2=BESTX2(I)
C     WRITE(3,933)I,IX2                     (THIS STMT PRINTS INTERIM RESULTS)    C
  810 CONTINUE
C     WRITE(3,934)                          (THIS STMT PRINTS INTERIM RESULTS)    C
      DO 820 I=1,NPRI
C     WRITE(3,935)I,BESTU(I)                (THIS STMT PRINTS INTERIM RESULTS)    C
  820 CONTINUE
C     WRITE(3,938)IIIII                     (THIS STMT PRINTS INTERIM RESULTS)    C
      DO 830 N4=1,NPRI
      SMALLU(N4)=BESTU(N4)
      IF(SMLSTU(N4)-SMALLU(N4))899,830,840
  830 CONTINUE
      GO TC 899
  840 DO 850 N5=1,NPRI
      SMLSTU(N5)=BESTU(N5)
  850 CONTINUE
      DO 860 N6=1,NVAR
      FINLX2(N6)=BESTX2(N6)
  860 CONTINUE
  899 CONTINUE
      WRITE(3,936)
      DO 990 I=1,NVAR
      IIIX2=FINLX2(I)
      WRITE(3,933)I,IIIX2
  990 CONTINUE
      WRITE(3,934)
      DO 995 I=1,NPRI
      WRITE(3,935)I,SMLSTU(I)
  995 CONTINUE
      GO TC 999
  996 CONTINUE
      WRITE(3,932)
      DC 997 M1=1,NVAR
      IVX2=X2(M1)
      WRITE(3,933)M1,IVX2
  997 CONTINUE
      WRITE(3,934)
      DO 998 M2=1,NPRI
      WRITE(3,935)M2,UNDER(M2)
```

```
 998  CONTINUE
      N3=N3+1
      WRITE(3,938)JJJJJ
      IF(N3.LE.NERCB)JJJJJ=0
      IF(N3.LE.NEFCE)GO TO 120
      GO TO 1001
 999  CONTINUE
      WRITE(3,938)JJJJJ
1001  CONTINUE
      IEND=IEND+1
      IF(IEND.LT.1)GO TO 1000
   1  FORMAT(4X,3I3)
   2  FORMAT(I1,3X,2I5,F11.0)
   3  FORMAT(4X,2I5,F11.0)
   4  FORMAT(8F10.0)
   5  FORMAT(I3)
   6  FORMAT(40I2)
 900  FORMAT(1H1,'NUMBER OF ROWS EQUAL',I3)
 901  FORMAT(1H ,'NUMBER OF VARIABLES EQUAL',I3)
 902  FORMAT(1H ,'NUMBER OF PRIORITIES EQUAL',I3)
 905  FORMAT(1H0,'DEVIATIONAL VARIABLE TO BE MINIMIZED (1=POS, 2=NEG),')
 906  FORMAT(1H ,'ROW NUMBER, PRIORITY LEVEL, AND WEIGHTING FACTOR:'/)
 907  FORMAT(1H ,T10,I2,4X,I3,5X,I2,F13.2)
 910  FORMAT(1H0,'ROW, COLUMN AND VALUE OF TECHNOLOGICAL COEFFICIENTS:'/
     1)
 911  FORMAT(1H ,T9,I3,4X,I3,F13.2)
 915  FORMAT(1H0,'RHS VALUE FOR EACH ROW:'/)
 916  FORMAT(1H ,T6,F13.2)
 920  FORMAT(1H0,'MATRIX OF COEFFICIENTS FOR VARIABLE SELECTION ROUTINE:
     1'/)
 921  FORMAT(1H ,T6,10E10.1)
 932  FORMAT(1H0,T65,'THE BEST SOLUTION SO FAR IS:'/)
 933  FORMAT(1H ,T75,'X(',I3,') = ',I2)
 934  FORMAT(1H0,T65,'    THE UNDERACHIEVEMENTS OF THE GOALS ARE:'/)
 935  FORMAT(1H ,T75,'THE UNDERACHIEVEMENT OF LEVEL ',I2,' IS',F12.3)
 936  FORMAT(1H0,T65,'THE BEST SOLUTION IS:'/)
 938  FORMAT(1H0,T65,'NUMBER OF ITERATIONS:  ',I6)
 940  FORMAT(1H0,'NUMBER OF PARTITIONED SUBPROBLEMS EQUALS',I3/)
 941  FORMAT(1H0,'THE FREE VARIABLES IN THIS SUBPROBLEM ARE:'/)
 942  FORMAT(1H ,T6,40I3)
 943  FORMAT(1H0,'SUBPROBLEM NUMBER',I3)
      STOP
      END
```

```
      SUBROUTINE USE1
C        THIS SUBROUTINE COMPUTES THE GOAL UNDERACHIEVEMENT LEVEL.          C
      COMMON MINDEV(40), LVLPRI(40), WTDEV(40), COEF(40,100), RHS(40)
      COMMON SUM(10,100), X1(100), X2(100), UNDER(10), UMIN(10)
      COMMON COMEAR(10), POSDEV(40), DEVNEG(40), NROW, NVAR, NPRI, II
      COMMON HOLD(10), HOLDX2(100), BESTX2(100), HOLDU(10), BESTU(10)
      COMMON TEMPU(10), HOLDX1(100), BESTX1(100), TEMPX1(100)
      COMMON TEMPX2(100), SWAPX1(100), SWAPX2(100), SUPRX1(100)
      COMMON SUPRX2(100), SWAPU(10), SUPRU(10), NROWS(40)
      COMMON NPROBM(100), SMALLU(10), SMLSTU(10), FINLX2(100)
      UMIN(II)=0.0
      DO 80 K=1,NROW
      POSDEV(K)=0.0
      DEVNEG(K)=0.0
      IF(LVLPRI(K).NE.II)GO TO 80
      TOTAL=0.0
      DO 10 L=1,NVAR
      TOTAL=COEF(K,L)*X2(L)+TOTAL
   10 CONTINUE
      DIFF=TOTAL-RHS(K)
      IF(DIFF)20,30,40
   20 DEVNEG(K)=ABS(DIFF)
      POSDEV(K)=0.0
      GO TO 50
   30 DEVNEG(K)=0.0
      POSDEV(K)=0.0
      GO TO 50
   40 POSDEV(K)=DIFF
      DEVNEG(K)=0.0
   50 IF(MINDEV(K)-1)60,60,70
   60 UMIN(II)=UMIN(II)+POSDEV(K)
      GO TO 80
   70 UMIN(II)=UMIN(II)+DEVNEG(K)
   80 CONTINUE
      RETURN
      END
```

```
NUMBER OF ROWS EQUAL 15
NUMBER OF VARIABLES EQUAL 10
NUMBER OF PRIORITIES EQUAL  6

DEVIATIONAL VARIABLE TO BE MINIMIZED (1=POS, 2=NEG),
ROW NUMBER, PRIORITY LEVEL, AND WEIGHTING FACTOR:

          2       1       1          1.00
          1       2       1          1.00
          1       3       2          1.00
          1       4       2          1.00
          1       5       2          1.00
          2       6       3          1.00
          2       7       4          1.00
          2       8       4          1.00
          2       9       4          1.00
          2      10       5          1.00
          2      11       5          1.00
          2      12       5          1.00
          1      13       6          1.00
          1      14       6          1.00
          1      15       6          1.00

ROW, COLUMN AND VALUE OF TECHNOLOGICAL COEFFICIENTS:

          1       9        1.00
          1      10        1.00
          2       9        1.00
          2      10        1.00
          3       1       10.00
          3       2       20.00
          3       3      100.00
          3       4       75.00
          3       5      200.00
          4       1       50.00
          4       4      150.00
          4       5       90.00
          4       6      100.00
          4       7       40.00
          4       8       10.00
          4      10       10.00
          5       1       10.00
          5       2        5.00
          5       3        1.00
          5       6       10.00
          5       7        4.00
          5       9       75.00
```

6	1	256.00
6	2	315.00
6	3	173.00
6	4	160.00
6	5	680.00
6	6	475.00
6	7	95.00
6	8	65.00
6	9	115.00
6	10	120.00
7	1	60.00
7	2	75.00
7	3	20.00
7	4	250.00
7	5	10.00
7	6	5.00
8	1	100.00
8	2	150.00
8	3	25.00
8	4	170.00
8	5	250.00
8	6	100.00
8	7	5.00
8	8	5.00
8	9	20.00
9	1	100.00
9	2	150.00
9	3	100.00
9	4	115.00
9	5	250.00
9	6	50.00
9	7	70.00
9	8	25.00
9	9	100.00
9	10	50.00
10	1	46.00
10	2	56.00
10	3	15.00
10	5	185.00
10	6	6.00
11	1	74.00
11	2	111.00
11	3	16.00
11	4	126.00
11	5	199.00
11	6	65.00
11	8	1.00

11	9	1.00
12	1	75.00
12	2	111.00
12	3	74.00
12	4	79.00
12	5	186.00
12	6	32.00
12	7	27.00
12	8	14.00
12	9	74.00
12	10	29.00
13	1	31.00
13	2	43.00
13	3	29.00
13	4	37.00
13	5	21.00
13	6	17.00
13	7	6.00
13	8	33.00
13	9	9.00
13	10	18.00
14	1	33.00
14	2	41.00
14	3	29.00
14	4	41.00
14	5	27.00
14	6	17.00
14	7	6.00
14	8	31.00
14	9	27.00
14	10	19.00
15	1	35.00
15	2	40.00
15	3	31.00
15	4	42.00
15	5	27.00
15	6	24.00
15	7	13.00
15	8	21.00
15	9	42.00
15	10	19.00

```
RHS VALUE FOR EACH ROW:
          1.00
          1.00
        250.00
        259.00
        300.00
       1800.00
        275.00
        600.00
        590.00
        187.00
        242.00
        267.00
         81.00
         84.00
         84.00
```

```
NUMBER OF PARTITIONED SUBPROBLEMS EQUALS  2

SUBPROBLEM NUMBER   1
THE FREE VARIABLES IN THIS SUBPROBLEM ARE:
       1   1   1   1   1   1   1   1   0   1
SUBPROBLEM NUMBER   2
THE FREE VARIABLES IN THIS SUBPROBLEM ARE:
       1   1   1   1   1   1   1   1   1   0



THE BEST SOLUTION IS:
          X(  1) =   1
          X(  2) =   1
          X(  3) =   0
          X(  4) =   0
          X(  5) =   1
          X(  6) =   1
          X(  7) =   0
          X(  8) =   0
          X(  9) =   0
          X( 10) =   1
   THE UNDERACHIEVEMENTS OF THE GOALS ARE:
          THE UNDERACHIEVEMENT OF LEVEL  1 IS        0.0
          THE UNDERACHIEVEMENT OF LEVEL  2 IS        0.0
          THE UNDERACHIEVEMENT OF LEVEL  3 IS        0.0
          THE UNDERACHIEVEMENT OF LEVEL  4 IS      125.000
          THE UNDERACHIEVEMENT OF LEVEL  5 IS        0.0
          THE UNDERACHIEVEMENT OF LEVEL  6 IS      163.000
NUMBER OF ITERATIONS:       29
```

APPENDIX C

Experiment 1
Data Analysis

The experimental design used in the first experiment of the case study reported in Chapter 4 required testing the hypothesis of no significant differences in mean benefits achieved for the portfolio strategies associated with the six models. Table C-1 shows the observed benefit values generated by the simulation routine, with the means ($\bar{x}_j$) and the variances (s_j^2) of each group, for j = 1, ..., 6 groups. A one-way factor analysis of variance (ANOVA) test was used to determine if there is a difference in the benefits achieved for the models. The ANOVA table for the observations is shown in Table C-2 and follows from Harnett and Murphy.[1] By employing the F statistic, the hypothesis of no difference in mean benefit values is rejected if F observed is greater than a critical F with significance level α, J-1 and N-J degrees of freedom. With α=.01, there *is a significant difference* between the means of the sample groups. To have confidence in this conclusion, the assumptions required by ANOVA must be met. That is, for the F statistic to perform correctly, there must be:[2]

1) Independence of statistical error terms.
2) Equality of population-error variances.
3) Normally distributed populations.

By using the random number generator through manipulation of the seed values in the manner described, independence within each population group is achieved. Hartley's F_{max} statistic was used to test for homogeneity of error variance. This test computed the F_{max} with 6 (number of variances) and 29 (number of observations within each group minus one) degrees of freedom as follows:[3]

Table C-1
Benefits Attained for Models 1-6

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	47.24	57.81	48.93	46.64	41.44	51.71
	52.47	53.91	44.92	51.40	45.76	52.30
	53.86	49.06	40.13	46.70	46.05	55.69
	51.61	52.44	44.32	54.22	43.03	48.60
	53.24	47.23	51.52	46.47	46.23	49.47
	53.75	51.68	40.02	49.86	45.42	52.81
	51.17	51.36	39.91	46.04	42.93	47.60
	50.52	58.59	46.54	45.04	50.02	50.52
	49.64	48.78	44.96	48.60	51.15	53.91
	46.34	51.44	43.07	47.93	41.72	53.78
	53.44	53.72	40.75	52.11	46.04	54.92
	49.07	48.13	51.32	47.84	46.31	50.49
	50.63	51.93	48.62	50.62	44.02	50.62
	50.99	47.48	44.21	50.45	45.39	54.69
	48.34	53.94	42.16	49.34	43.39	52.21
	51.66	45.46	48.24	51.58	45.86	54.14
	44.41	53.81	47.50	45.15	44.35	51.67
	50.20	49.17	48.09	50.39	40.85	52.54
	48.79	52.03	45.88	47.83	40.72	53.91
	47.70	50.86	47.37	48.86	45.19	53.80
	48.57	50.27	42.92	57.04	48.26	52.75
	45.88	47.46	44.55	52.23	41.04	53.17
	50.75	47.05	42.43	45.03	41.92	53.64
	52.09	45.24	43.07	50.85	46.88	47.59
	45.72	47.85	47.33	50.17	43.05	49.28
	48.49	53.46	46.73	46.97	39.17	53.02
	46.76	45.43	46.17	53.03	41.84	53.38
	52.35	52.97	42.57	49.37	47.72	50.43
	48.90	45.89	42.57	52.12	43.89	48.76
	50.31	48.49	39.45	52.69	45.31	49.92
$\bar{x}_j$	49.830	50.430	44.875	49.552	44.498	51.911
s_j^2	6.537	12.214	10.973	8.543	7.914	4.969

Table C-2
ANOVA Table

Source of Variation	(1) Sum of Squares (SS)	(2) Degrees of Freedom (df)	(3) Mean Squares (1)/(2)	F (a)/(b)
Between Samples (a)	1421.716	J-1 = 5	284.343	33.354
Error (b) (Within samples)	1483.348	N-J = 174	8.525	
Total	2905.064	N-1 = 179		

$$F_{max} = s_j^2 \text{ largest} / s_j^2 \text{ smallest} = \qquad (c.1)$$

$$= 12.214 / 4.969 \qquad = 2.458$$

The hypothesis of homogeneity of variance is rejected if F_{max} is greater than the tabled value for F_{max}, as developed from the F_{max} distribution.[4] With $\alpha = .01$, the critical F_{max} is 3.73 and therefore, the hypothesis is not rejected. Finally, since the F statistic is robust to violations of nomality, all requirements of ANOVA are met.

Having determined that there is an overall difference in the sample group means, the next test is to determine which means are different through multiple comparison analysis. A simple multiple comparison test developed by Tukey in 1953,[5] called the Honestly Significantly Differences (HSD) test, is used in this study. For the HSD test to perform correctly, the same assumptions required by the F statistic used in ANOVA design are also required. Since the HSD test is robust to violations of normality, this and the other two assumptions are again met.[6] The differences among the means of the sample groups from Table C-1 are arrayed as shown in Table C-3. A comparison between two means is significant if it exceeds an HSD which is given by:

$$HSD = q_{(\alpha;\ J,\ N-J)} \text{ (Mean Square Error/ n)}^{1/2} \qquad (c.2)$$

$$= 4.76 \ (.533) = 2.537$$

The value of q is obtained from the distribution of the studentized range statistic.[7] For this test, $\alpha = .01$ and the degrees of freedom

Table C-3
Differences Among Mean
Benefit Attainment Levels

	$\bar{X}_6$	$\bar{X}_2$	$\bar{X}_1$	$\bar{X}_4$	$\bar{X}_3$	$\bar{X}_5$
$\bar{X}_6$	-	1.481	2.081	2.359	7.036*	7.413*
$\bar{X}_2$		-	.600	.878	5.555*	5.932*
$\bar{X}_1$			-	.278	4.955*	5.332*
$\bar{X}_4$				-	4.677*	5.054*
$\bar{X}_3$					-	.377
$\bar{X}_5$						-

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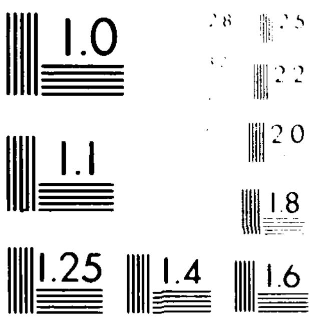
1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5

are J= 6, and N-J= 174. The values marked with an asterisk in Table C-3 indicate a significant difference between corresponding means.

Footnotes

[1]D. L. Harnett, and L. L. Murphy, Introductory Statistical Analysis (Reading Mass.: Addison-Wesley Publishing Co., Inc., 1975), Chap. 9.

[2]R. E. Kirk, Experimental Design: Procedures for the Behavioral Sciences (Belmont, Cal.: Brooks/Cole Publishing Co., 1968), p. 61.

[3]H. O. Hartley, "The Maximum F-ratio as a Short-cut Test for Heterogeneity of Variance," Biometrika, Vol. 37 (1950), pp. 308-312.

[4]Kirk, Table D.10, p. 536.

[5]Ibid., p. 88.

[6]Ibid.

[7]Ibid., Table D.7, pp. 531-532.

APPENDIX D

Experiment 2
Data Analysis

The experimental design used in the second experiment of the case study reported in Chapter 4 required testing the hypothesis of no significant differences in the benefits achieved for the portfolio strategies associated with the two models versus the alternate hypothesis that the benefit values of model 1A are greater than those of 1B. Table D-1 shows the observed benefit values generated by the simulation routine. The statistical technique used to test this hypothesis is the t test for differences between matched samples.[1] This test requires computation of the difference scores of the benefit values for each model as shown in Table D-1. The hypothesis of no difference between the samples is rejected if the observed t statistic, of the form:

$$t_{n-1} = t_{29} = (D - 0) \;/\; (s_D \;/\; (n)^{1/2}) = 5.902 \qquad \text{(d.1)}$$

is greater than a critical ratio of a one sided test with an α level of .01.[2] In this case, the critical t is 2.765 and the hypothesis of no difference is rejected.

Table D-1
Difference Scores on
the Benefits Attained (10^6 $)

Observation	(1) Model 1A Benefits	(2) Model 1B Benefits	D_i (1) - (2)
1	54.24	53.88	.36
2	49.84	48.69	1.15
3	51.37	47.30	4.07
4	48.31	46.01	2.30
5	50.18	47.36	2.82
6	42.58	48.80	3.78
7	54.74	52.71	2.03
8	46.33	44.96	1.37
9	50.22	46.87	3.35
10	50.41	50.39	.02
11	49.35	49.68	- .33
12	50.92	49.02	1.90
13	53.62	49.66	3.96
14	54.49	50.69	3.80
15	49.56	46.99	2.57
16	53.24	52.12	1.12
17	51.85	49.95	1.90
18	49.93	48.02	1.91
19	48.79	50.07	-1.28
20	52.79	48.43	4.36
21	50.76	49.99	.77
22	54.12	55.01	- .89
23	50.92	47.62	3.30
24	52.39	52.88	- .49
25	47.59	43.46	4.13
26	54.14	53.96	.18
27	50.19	46.00	4.19
28	45.03	44.68	.35
29	46.28	45.96	.32
30	47.30	45.70	1.60
Mean:	50.716	48.895	1.821
Standard Deviation:	2.633	2.952	1.690

Footnotes

[1]D. L. Harnett, and J. L. Murphy, Introductory Statistical Analysis (Reading, Mass.: Addison-Wesley Publishing Co., Inc., 1975), pp. 363-366.

[2]A one sided test is used since the alternate hypothesis is directional.

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